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PROCEEDINGS OF OSD AIRCRAFT ENGINE DESIGN & LIFE CYCLE COST SEM--ETC(U)
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LEVEL II

(6) PROCEEDINGS OF OSD

AIRCRAFT ENGINE DESIGN & LIFE CYCLE COST SEMINAR

HELD AT
NAVAL AIR DEVELOPMENT CENTER
WARMINSTER, PENNSYLVANIA
MAY 17, 18 & 19,
1978

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(12) 383

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KEYNOTE ADDRESS

By

Mr. A. S. Atkinson
Executive Director
for Acquisition
Management, NAVAIR

GOOD MORNING, I AM VERY GLAD TO BE HERE TO SPEAK TO YOU ON ONE OF THE MOST CRUCIAL CHALLENGES FACING THE DEFENSE DEPARTMENT TODAY - THAT OF FINDING WAYS TO IMPROVE RELIABILITY, AND LOWER LIFE CYCLE COSTS WHILE MAINTAINING PERFORMANCE.

INCREASED EMPHASIS IS BEING PLACED ON IMPROVED RELIABILITY AND MAINTAINABILITY, LOWER LIFE CYCLE COST AND INCREASED READINESS. TO MEET THESE OBJECTIVES WE MUST CHANGE OUR PREVIOUS METHODS OF DOING BUSINESS IN THE DEVELOPMENT AND ACQUISITTON OF NEW ENGINES.

BEFORE THE CENTER LINE OF A NEW AIRCRAFT ENGINE IS DRAWN THERE MUST BE A CLOSE WORKING RELATIONSHIP AMONG THE REQUIREMENTS ACTIVITY (CNO), THE ACQUISITION ACTIVITY (AIR-05), THE LOGISTICIAN (AIR-04) AND THE USERS (THE FLEET).

THE FIRST THING TO BE DETERMINED IS THE MISSION. THE REQUIREMENTS ACTIVITY MUST SET FORTH THE WEAPONS SYSTEM MISSION OR THE THREAT TO BE MET. THE USERS WILL ADVISE THE DEVELOPING ACTIVITY AS TO HOW THE AIRCRAFT WILL BE FLOWN IN ORDER TO MEET THE STATED MISSION. THE LOGISTICIAN WILL ADVISE THE ACQUISIITON ACTIVITY AS TO THE MAINTENANCE PHILOSOPHY. THE RELIABILITY REQUIREMENTS FOR THE ENGINE WILL BE SET SO THAT THE TOTAL WEAPONS SYSTEM RELIABILITY CAN BE MET. THIS INFORMATION WILL BE USED BY THE ACQUISITION ACTIVITY TO ESTABLISH THE PROPER DESIGN AND TEST REQUIREMENTS TO INSURE THAT THE ENGINE WILL MEET ALL THE PERFORMANCE, RELIABILITY AND MAINTAINABILITY REQUIREMENTS AT THE LOWEST LIFE CYCLE COST.

INDUSTRY MUST BE AWARE OF THE TOTAL REQUIREMENTS PACKAGE SO THAT ALL

ELEMENTS OF DESIGN, I.E., PERFORMANCE, RELIABILITY, MAINTAINABILITY, LIFE CYCLE COST, ETC., CAN BE TAKEN INTO CONSIDERATION FROM INCEPTION. THE WHOLE PROCESS MUST BE AN ITERATIVE ONE, NOT ONLY WITHIN THE NAVY BUT ALSO WITH INDUSTRY.

THE NAVY IS MOVING TOWARD THIS NEW APPROACH, MORE CLOSELY DUPLICATING OPERATIONAL STRESSES IN ENGINE TESTING TO OVERCOME THE HISTORICAL SPATE OF ENGINE PROBLEMS OCCURRING WITHIN THE FIRST FEW YEARS OF ENGINE DEVELOPMENT. NAVAIR HAS INITIATED THIS EFFORT AND ON-GOING STUDY RESULTS HAVE CONFIRMED PREVIOUS SUSPICIONS THAT PAST DEVELOPMENT TESTING HAS NOT KEPT PACE WITH ADVANCEMENTS IN TECHNICAL DISCIPLINES NOR MATCHED THE DUTY CYCLE EXPERIENCED BY THE ENGINE IN ACTUAL SERVICE.

THE NAVY HAS USED THIS TECHNIQUE TO DEVELOP A 750 HOUR SIMULATED MISSION ENDURANCE TEST (SMET) FOR THE F404 ENGINE IN THE F-18 AND A 1000 HOUR SMET FOR THE T700 ENGINE IN THE LAMPS MK III. IN ADDITION, TF30 ENGINE IMPROVEMENT CHANGES ARE BEING TESTED TO A 1000 HOUR SMET. THE NEXT NEW ENGINE DEVELOPED WILL BE DESIGNED AND TESTED TO A 1000 HOUR SMET. THIS WILL BE THE FIRST DEVELOPMENT PROGRAM WITH THE ALL "NEW LOOK", I.E., SMET, LOW CYCLE FATIGUE TEST, ACCELERATED SERVICE TEST, WITH AN OVERALL REQUIREMENT OF LIFE CYCLE COST.

AN ADDITIONAL BENEFIT TO THE NAVY WILL BE THE ACCURATE CONCEPTUAL, PRELIMINARY AND DETAILED DESIGN GUIDANCE TO THE ENGINE INDUSTRY WHICH CLAIMS THAT LESS THAN SATISFACTORY LEVELS OF ENGINE RELIABILITY ARE ATTRIBUTABLE TO ERRONEOUS INITIAL DESIGN GUIDANCE.

AFTER THE MISSION, PERFORMANCE PARAMETERS, MAINTENANCE PHILOSOPHY AND RELIABILITY REQUIREMENTS ARE SET FORTH, THE LIFE CYCLE COSTS CAN BE PROJECTED. ALTHOUGH AIRCRAFT ENGINES ARE A WEAPONS SUBSYSTEM THEY ACCOUNT ANNUALLY FOR OVER $4 BILLION DOLLARS IN THE DEVELOPMENT, ACQUISITION AND OPERATING AND SUPPORT PHASES OF THEIR LIFE CYCLE. HISTORICALLY, DECISIONS AFFECTING NAVAL AIRCRAFT ENGINES HAVE BEEN MADE EMPHASIZING PERFORMANCE WITH LITTLE CONSIDERATION OF COST. TODAY'S ENVIRONMENT, BEING QUITE DIFFERENT, EXACTS A CONSCIOUS UNDERSTANDING OF THE COST IMPLICATIONS OF SPECIFIED PERFORMANCE REQUIREMENTS. THESE IMPLICATIONS NECESSITATE AN IN-DEPTH UNDERSTANDING OF COSTS DURING THE PHASES OF AN ENGINES LIFE CYCLE. IT IS ANTICIPATED THAT FUTURE REQUIREMENTS WILL DEMAND ENGINE COMPONENT (I.E., COMPRESSOR, BURNER, TURBINE, ETC.) LIFE CYCLE COST VERSUS PERFORMANCE TRADE-OFFS DURING THE CONCEPTUAL PHASE PRIOR TO FULL SCALE DEVELOPMENT.

THE HISTORICAL DATA REQUIRED TO LAY THE FOUNDATION FOR FUTURE ENGINE COST ANALYSIS IS NOT PRESENTLY AVAILABLE IN A SINGLE DATA SYSTEM AND JUSTIFIABLE CONCERN HAS BEEN EXPRESSED BY BOTH INDUSTRY AND GOVERNMENT AS TO WHETHER THE NECESSARY DATA IS PRESENTLY BEING COLLECTED, AND IF COLLECTED, RETAINED. FURTHER CONCERN HAS BEEN MANIFESTED AS TO THE ACCURACY OF AVAILABLE ENGINE OPERATING AND SUPPORT COST DATA, SINCE THE DATA COLLECTION OBJECTIVES FOCUS ON THE WEAPONS SYSTEM AT THE EXPENSE OF THE SUBSYSTEM. FUTURE JUSTIFICATION OF MILITARY WEAPONS SYSTEMS, AND THEIR MAJOR SUBSYSTEMS WILL NOT WITHSTAND SCRUTINY OF POORLY DEFINED SUBSYSTEM COSTS THAT RESULT IN UNCERTAIN SYSTEM LIFE CYCLE COSTS.

AIRCRAFT ENGINE DEVELOPMENT AND ACQUISITION COST PROJECTION METHODS ARE WELL IN HAND PRIMARILY DUE TO THE EFFORT AND RESOURCES EXPENDED BY THE AIRCRAFT ENGINE COMMUNITY DURING RECENT YEARS. ON THE OTHER HAND, THE OPERATING AND SUPPORT COSTS AND THE PROJECTION OF THESE COSTS ARE THE LEAST UNDERSTOOD SEGMENT OF AN ENGINES LIFE CYCLE COST. IN ORDER TO PROJECT HOW CERTAIN PERFORMANCE PARAMETERS AND ENGINE GEOMETRY EFFECT LIFE CYCLE COST WE MUST KNOW WHAT THE CURRENT ENGINE DESIGNS ARE COSTING US IN THE OPERATING AND SUPPORT PHASE. WE MUST KNOW WHAT IS FAILING AND WHY, SO THAT WE CAN PROPERLY DESIGN AND DEVELOP THE NEXT GENERATION OF NAVY ENGINES. TO THIS END WE MUST HAVE A MORE ACCURATE REPORTING SYSTEM FOR PROPULSION DOWN TO THE COMPONENT LEVEL. WE MUST HAVE A CENTRAL POINT FOR COLLECTING AND MANAGING ALL OPERATING AND SUPPORT PROPULSION COSTS. WE MUST HAVE BETTER DATA WITH WHICH TO DEFINE PROBLEM AREAS AND THEREBY WE CAN BETTER DEFINE TEST REQUIREMENTS.

THIS SEMINAR IS AN ATTEMPT TO TAKE A SPECIFIC HARDWARE ITEM, AIRCRAFT PROPULSION, AND BRING TO BEAR THE EXPERTISE OF BOTH TECHNICAL AND COST ESTIMATING EXPERTS FROM BOTH INDUSTRY AND GOVERNMENT TO CONCENTRATE ON THE OVERRIDING PROBLEMS OF REDUCING OUR LIFE CYCLE COSTS IN THE FUTURE. IT IS ONLY BY OUR OWN INDIVIDUAL EFFORTS THAT PROGRESS CAN BE MADE. TWO DECADES AGO THERE WERE FEW COST ANALYSTS. AND ALTHOUGH I BELIEVE THE COST ANALYSTS HAVE DONE A CREDITABLE JOB CONSIDERING WHAT THEY HAD TO WORK WITH, I THINK WE HAVE DRIFTED TOWARDS A POLICY OF SEPARATING OUR TECHNICAL AND COST ESTIMATING FUNCTIONS WITHIN THE DEFENSE DEPARTMENT. IT HAS ALLOWED THE ENGINEERS TO FORGET THE COST IMPACTS TOO EASILY. RECTIFYING THIS SITUATION IN THE ENGINE COMMUNITY IS A CHALLENGE THAT MUST BE MET.

YOU AND YOUR PREDECESSORS HAVE PRODUCED THE PACING ITEM, THE PROPULSION SYSTEM, IN WHAT ARE ACKNOWLEDGED AS THE FINEST, MOST TECHNICALLY ADVANCED AIRCRAFT IN THE WORLD. OUR DOMINATION OF THE WORK MARKET IN BOTH MILITARY AND CIVILIAN AIRCRAFT IS PROOF OF THIS GREAT EFFORT.

I WOULD CHALLENGE YOU TODAY TO ALSO LEAD THE WAY IN OVERCOMING WHAT IS JUST AS CRUCIAL A FRONTIER, THAT OF HOW TO PROPERLY IMPLIMENT A PHILOSOPHY OF DESIGNING A MORE RELIABLE ENGINE AT AN OVERALL LOWER LIFE CYCLE COST.

IN CLOSING I WOULD LIKE TO THANK YOU FOR ASKING ME TO ADDRESS THIS SEMINAR. I BELIEVE IT WILL BE FRUITFUL TO ALL PARTICIPANTS AND COULD ALSO BE A MODEL FOR SIMILAR MEETINGS ON OTHER HARDWARE ITEMS IN THE FUTURE.

NAVY ENGINE COST METHODOLOGY

L. T. FINIZIE

I. INTRODUCTION

The NADC (Naval Air Development Center) has done engine cost estimating work on development, production, and operating and support costs. Although production costs were first studied by NADC, in this presentation development costs will be considered first since they occur first. Production costs will be discussed next and, O&S (Operation and Support) costs will be discussed last.

II. DEVELOPMENT COSTS

Although it has been only two and a half years since the last DOD (Department of Defense) sponsored engine cost seminar held at NADC, it is considered appropriate to review the assumptions upon which the development costs were based. Figure 1 shows the change in TIT (turbine inlet temperature) with time. The line in the region of 1980 can be seen to be straight. For this reason it is assumed that the relationship between the development cost at the MQT (model qualification test) and calendar time can still be represented by a straight line as shown in figure 2. Since the number of new engines developed for the military has been drastically reduced, it will be many years before sufficient engines are developed significantly to modify the development cost estimating relationship in use at the present. The plot shown in figure 3 indicates that four different engines each with a TIT of 2060° Rankine were needed to make the analysis. It is unlikely that such a large selection of engines will be available for analysis in the immediate future. MQT, TIT and the existence of an afterburner are shown in figure 4 to be the principal engine parameters determining engine development cost. Additionally an accuracy within ten percent is shown to be typical of almost all of the engines used in the data base. A one sigma value of 23 million dollars as shown on figure 4 appears high but compared to an average development cost for a fighter engine of 500 million dollars it is less than five percent.

III. PRODUCTION COSTS

The first engine cost study assigned to NADC by NAVAIR (Naval Air Systems Command) was for production engines. The changing composition of engine materials caused the rapid increase in nickel alloys and the consequent increase in cost as shown in figure 5. These changes began about 1955 and rapidly increased through the sixties. Rapid changes

meant rapidly increasing costs and a method to predict cost was needed. Mr. R. J. Maurer who first tasked NADC with the production cost study was aware of the large amount of material used during the manufacturing process. The relatively small amount of the raw material that becomes the finished engine is shown in figure 6. Since approximately sixty percent of an engine is made of forgings, considerable machining is required to produce a finished part. On some forgings the ratio of the input material to the output material can be as high as ten to one. In order to allow for the effect on cost of large amounts of expensive nickel alloys, that are needed to produce a gas turbine engine, a material factor criterion was developed by NADC with the assistance of the P&W (Pratt and Whitney Aircraft Corporation).

This criterion, called the Maurer factor in posthumous honor of its originator, is computed from the weighting factors shown in figure 7. These weighting factors are the product of the ratio of the cost of the material to the cost of low carbon steel, and the ratio of the cost of machining the material to the cost of maching low carbon steel. From the samples shown it can be seen that the classification "A" consists of those materials containing some chromium and a small percentage of nickel, the other materials increase in nickel content up to the "D" classification which contains as much as 80% nickel. Titanium is in a separate classification. The computation for the Maurer factor consists then of simply making a weighted summation of all the raw materials used in the manufacture of an engine. This summation is shown in figure 8. Forty-two engines were used in the correlation between Maurer factor and cost as shown in figure 9. These engines were produced by the General Electric Company, the P&WA Company, Detroit Diesel Allison Division and the Rolls-Royce Company. The one sigma measure of variation is seen to be $31,00 which is a relatively small percentage of the one million dollar manufacturing cost typical for a Navy fighter engine. For smaller engines another correlation has been developed with a proportionally smaller sigma. Weighting factors for the materials comprising the Maurer factor have been continuously updated to reflect the changing relative cost of materials and the relative cost of machining. Figure 10 shows the correlation resulting from the use of weighting factors updated to 1977. It is immediately apparent that the correlation as measured by both the coefficient of correlation and sigma has not improved. Offsetting this slight deterioration in accuracy is the fact that the weighting factors now can be determined by formula resulting in more consistent material classifications. In the absence of accurate historical material costs, dating to the beginning of the cost study, extrapolations were made from relatively recent cost data. It is expected that as more accurate correction factors are applied to the early historical cost of materials the cost correlation will improve.

Generally a detailed bill of material is not available during the early development stage of an engine. It is then necessary to use the parameters such as those shown in figure 11 of ω_a (airflow), TIT, and the existence of an afterburner $\delta_{A/B}$. It can be seen that estimated and actual Maurer factors agree within ten percent for engines the size of those powering Navy fighters. The Maurer material factor has been successfully applied to turbofans, turbojets, turboprops and turboshafts

when evaluating different power plants for proposed applications in Naval aircraft. These applications as well as the parameters found significant to the cost are shown in figure 12. The NASA (National Aeronautics and Space Administration)-Navy lift fan program is probably the best example to date of the value of the application of the Maurer factor cost methodology in making an evaluation between two competing power systems. The aircraft shown in figure 13 illustrates the arrangement of one fwd nose fan and two gas turbine engines aft of the wing. The gas system drives the nose tip fan with hot gases while the shaft system drives the nose fan through shafts and gears. On first thought hot combustion gases appear a logical way to provide power to the nose fan. However, even a very preliminary analysis of the bill of material for the gas system discloses the use of a considerable amount of high nickel alloys.

Review of the competing shaft driven system revealed little special alloys required since the necessary power was being transmitted by shafts at ambient temperature. However, several hundred pounds of titanium used in the motor mounts were changed in the shaft driven design since the weight advantage over aluminum was shown not to be cost effective. Examination of the material lists for both of the competing designs disclosed areas in which significant savings were made early in the design phase by using less expensive materials.

IV. OPERATING AND SUPPORT COSTS

O&S costs of weapons systems recently have become of concern to the military services. Since engine cost respresents a significant component of the cost of an aircraft weapon system, it is necessary to compute the complete life cycle costs of engines. Because development and production costs can be computed with an accuracy of ten percent, it is the operating and support costs that are presently receiving the principal concern of the Navy so that greater confidence can be placed on total life cycle costs.

In an attempt to simulate the maintenance path of gas turbine engines several programs have been developed as shown in figure 14. The vane and blade model can be seen to be fairly large since it comprises 2000 cards and uses 100,000 octal core units. These programs were developed to do more than compute operation and support costs since these costs can be approximated by computing the total flight hours and fuel costs. Multiplying the total number of operational engines by the number of scheduled flight hours for each aircraft and then by an average cost per flight hour obtains the total maintenance cost. To this cost is added fuel, oil, and lubricants. The program developed for studying operation and support costs, however, provides numerous data that characterizes the maintenance process. All of the significant events that occur during an engine's maintenance cycle are recorded and summaries printed by specified schedule. Many time periods, generally in days, are specified in the program inputs such as those shown in figure 15. Most of these inputs remain constant during the simulation although they

can be changed if desired. Simulation period is generally set at twenty years; the reporting period once a year. Time to perform maintenance actions are characteristic of the particular engine examined. Examples are the times required to perform an overhaul at the intermediate maintenance activity and at the depot. Other time periods are determined from the operating schedule such as the maximum engine flight hours per month. All these time periods control the rate at which the engines flow through the maintenance path. Other quantities and ratios are input to reflect the known maintenance history of specific aircraft and engines. These quantities are shown in figure 16 and give the rate at which flying time is accumulated, the rate at which engines can be repaired, the fraction of the total number of engines sent to the depot in addition to the intermediate repair activity, and the fraction of engines that are attrited.

Time before failure ranging from zero to an input maximum for a variety of events requiring maintenance is computed from a random input number. Five different failure curves may be used to make this computation for time before failure. Additionally, failure time may also be computed from cumulative flight hours. A daily computation of each engine's operating time is made and this time is compared with failure times previously computed and assigned to a particular engine. If the operating time is less than that at which a failure has been computed, the increment in flying hours caused by an additional day is recorded and another comparison made with the predicted failure times. This daily accumulation continues until it causes the time on an engine to exceed the minimum predicted failure time assigned to that engine. A record is then made of the time flown before failure and a computation is made using a random number input to determine the time until the next failure. The failure curves shown in figure 17 can be used in this simulation.

Periodically the O&S program prints results of many of the maintenance events. Figure 18 shows aircraft maintenance history. Aircraft flying, attrited or in the process of maintenance at the end of the report period are shown. Similiar statistics are provided in figure 19 and 20 for the engine. Total numbers and daily rates of repairs are provided for both intermediate and depot maintenance. Removals, inspections and delays can be assessed when comparing engines. A breakdown of the total number of failures by cause is given in figure 21. These reasons for failure provide insight when analyzing differences in engine maintenance cost. Additional data relative to engines in maintenance is provided in figure 22. Cumulative engine flight hours is the program output that provides a quick evaluation of engine reliability. After the total flying hours have been determined it is possible to compute a cost per flight hour. This cost at the present time varies from $150/hr as shown in figure 23 to a possible $556-699/hr as shown in figure 24. Preliminary investigations by P&WA at intermediate and depot repair installations such as those at Oceana and the Naval Air Rework Facility at Norfolk, Virginia indicate the costs may be more closely approximated by the higher figure. A contract has been issued to P&WA by NADC and sponsored by NAVAIR to obtain the data available as outlined in figure 25. It can

be seen that module cost data is not retained from more than 3-4 years. Figure 26 shows maintenance costs for the TF30-P-412 engine for repairs and overhauls. Quantities are given for each maintenance action and weighted averages computed as a function of time. These costs are representative of those obtained from the 3M and NARF data. Time between overhaul which is an indicator of engine reliability is shown in figure 27 to be around 200 hours. This time is considerably less than that used in many simulations comparing engine O&S costs. When the purpose of the simulation is to compare engines such inaccuracies do not invalidate comparisons, however, when O&S costs are needed for cost effective trade-offs absolute costs are required. For this reason maintenance cost data and time between repair actions is presently being sought.

V. CONCLUSIONS

In order to compute more accurate O&S costs more accurate repair costs of components as well as complete engines are required. The purpose of the current contract with P&WA is to obtain these costs. An outline of the tasks comprising the content of the contract is shown in figure 28. In addition to repair costs the Navy seeks a method to compute these costs as well as recommendations to reduce existing costs. Hopefully the performance of the contract by P&WA will provide the necessary information to make possible the prediction of O&S costs to the same degree of accuracy that has been achieved with development and production costs.

VI. ACKNOWLEDGEMENTS

The NADC Engine Cost Study was first sponsored by Mr. R. J. Maurer of the NAVAIRSYSCOM. Subsequent direction was provided by Messrs. A. S. Atkinson and A. Pressman. Much of the work on the Engine Cost Methodology was done by Messrs. T. J. Brennan and J. L. Birkler.

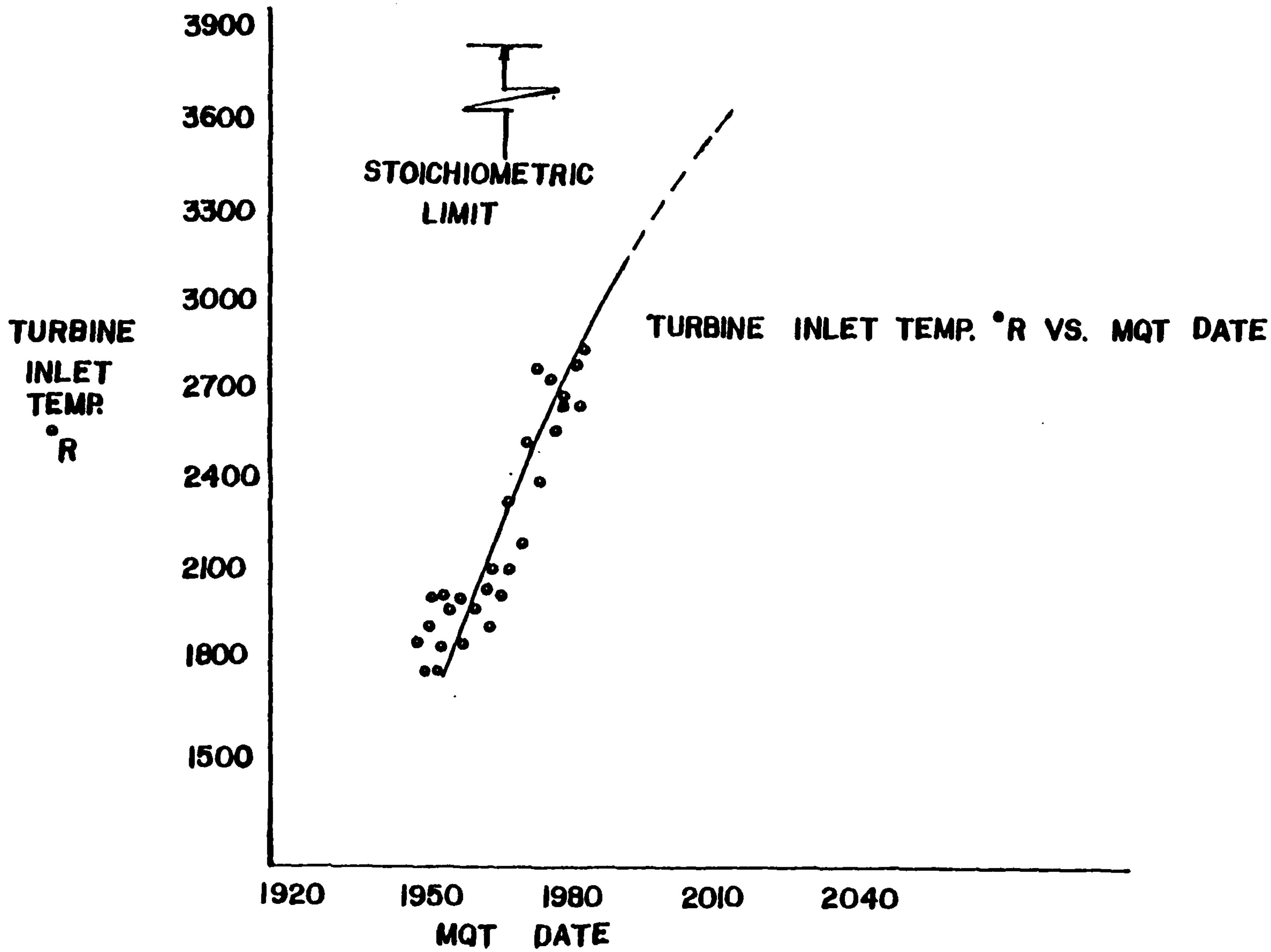

FIGURE I TECHNOLOGICAL FORECASTING

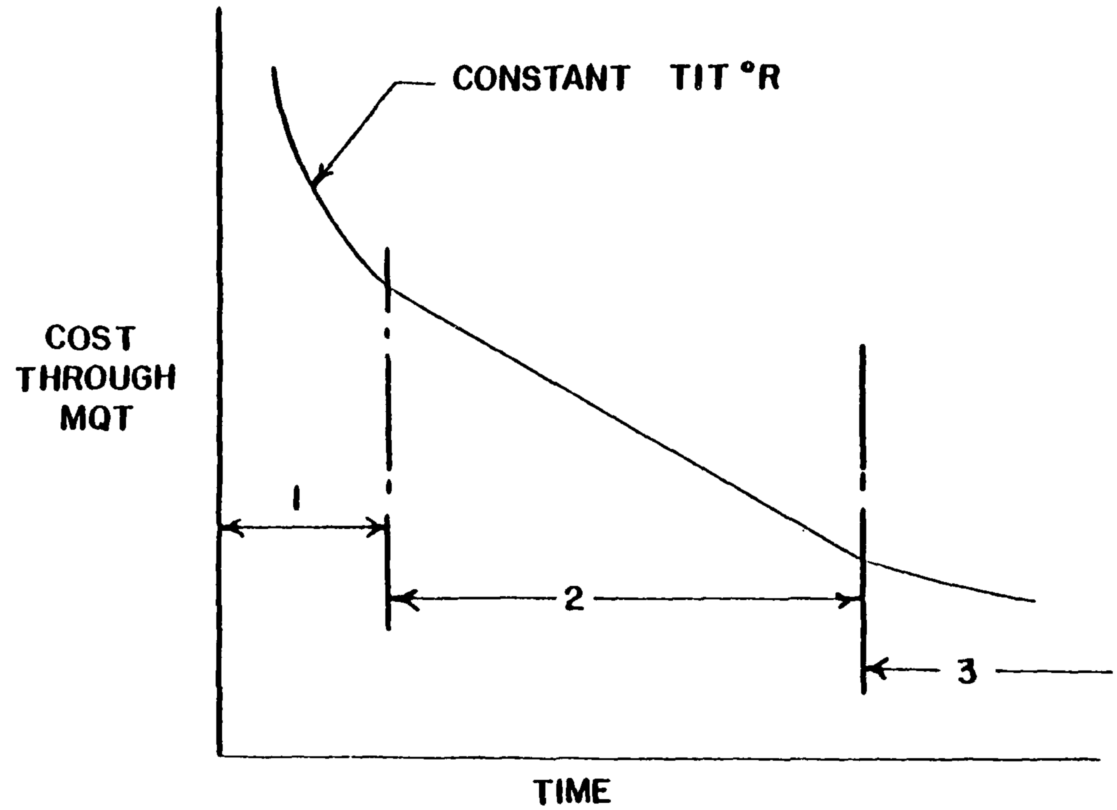

FIGURE 2 COST-TIME RELATIONSHIP FOR CONSTANT TURBINE INLET TEMPERATURE

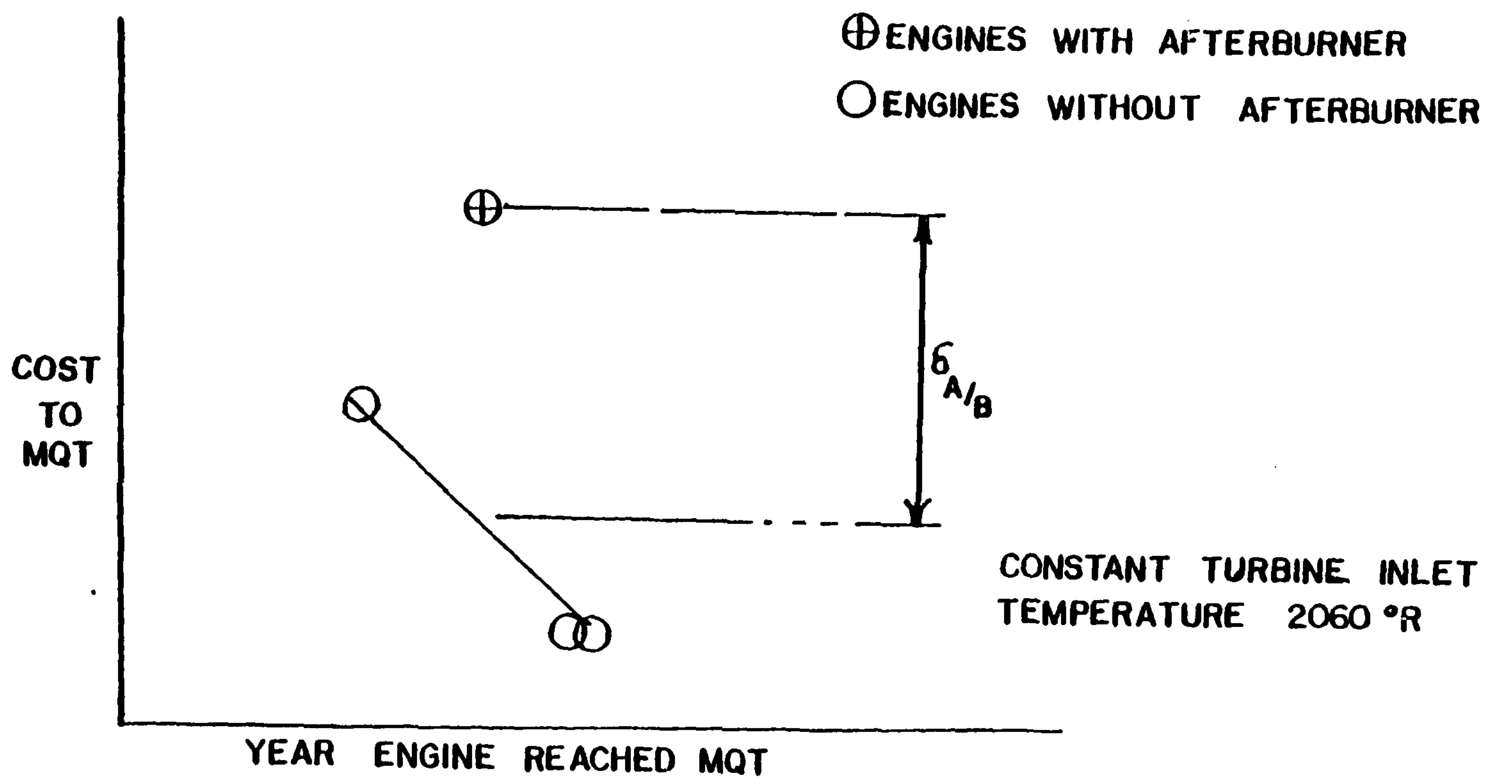

FIGURE 3 COST VS TIME AT CONSTANT TEMPERATURE

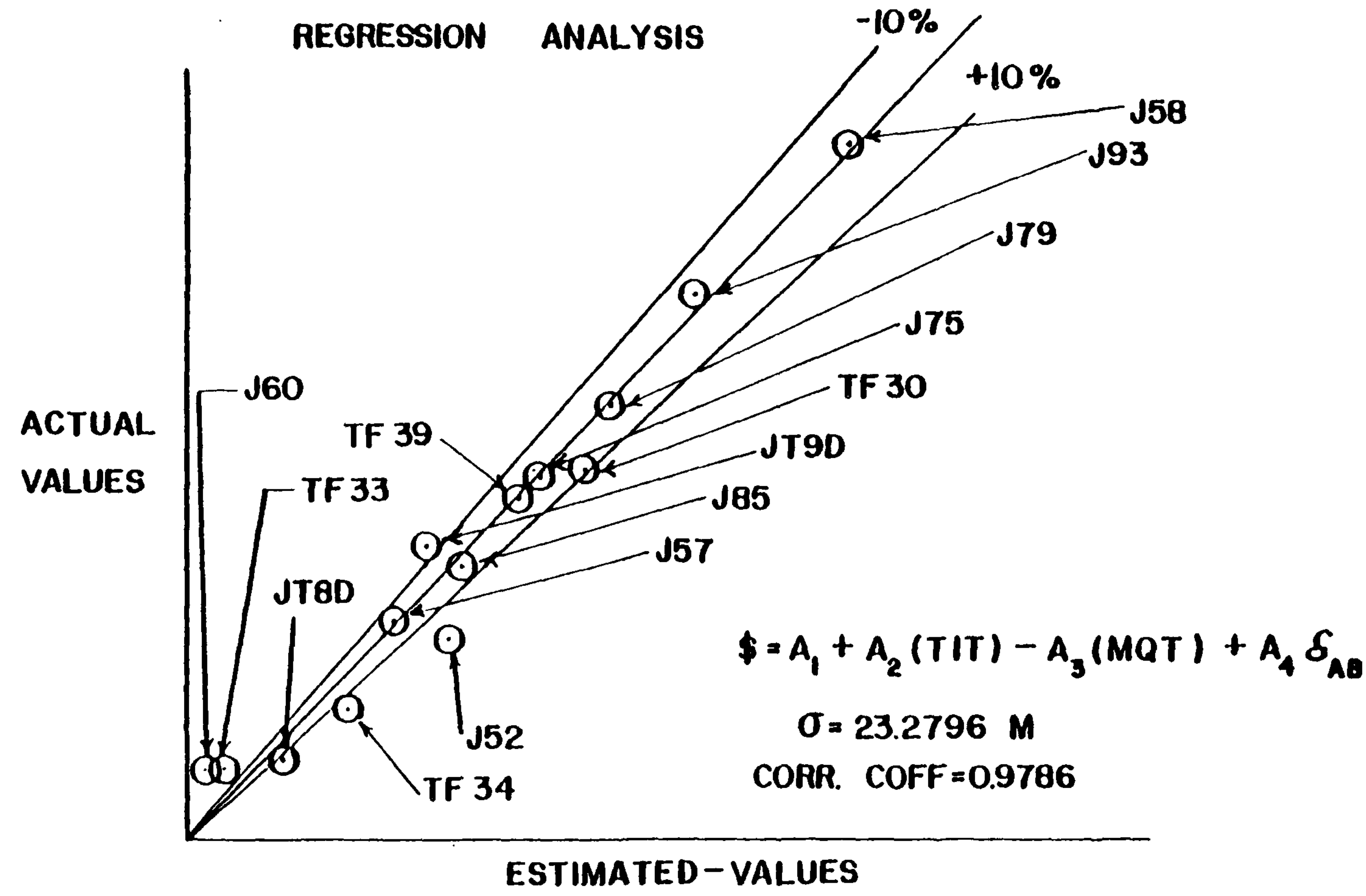

FIGURE 4 DEVELOPMENT COSTS

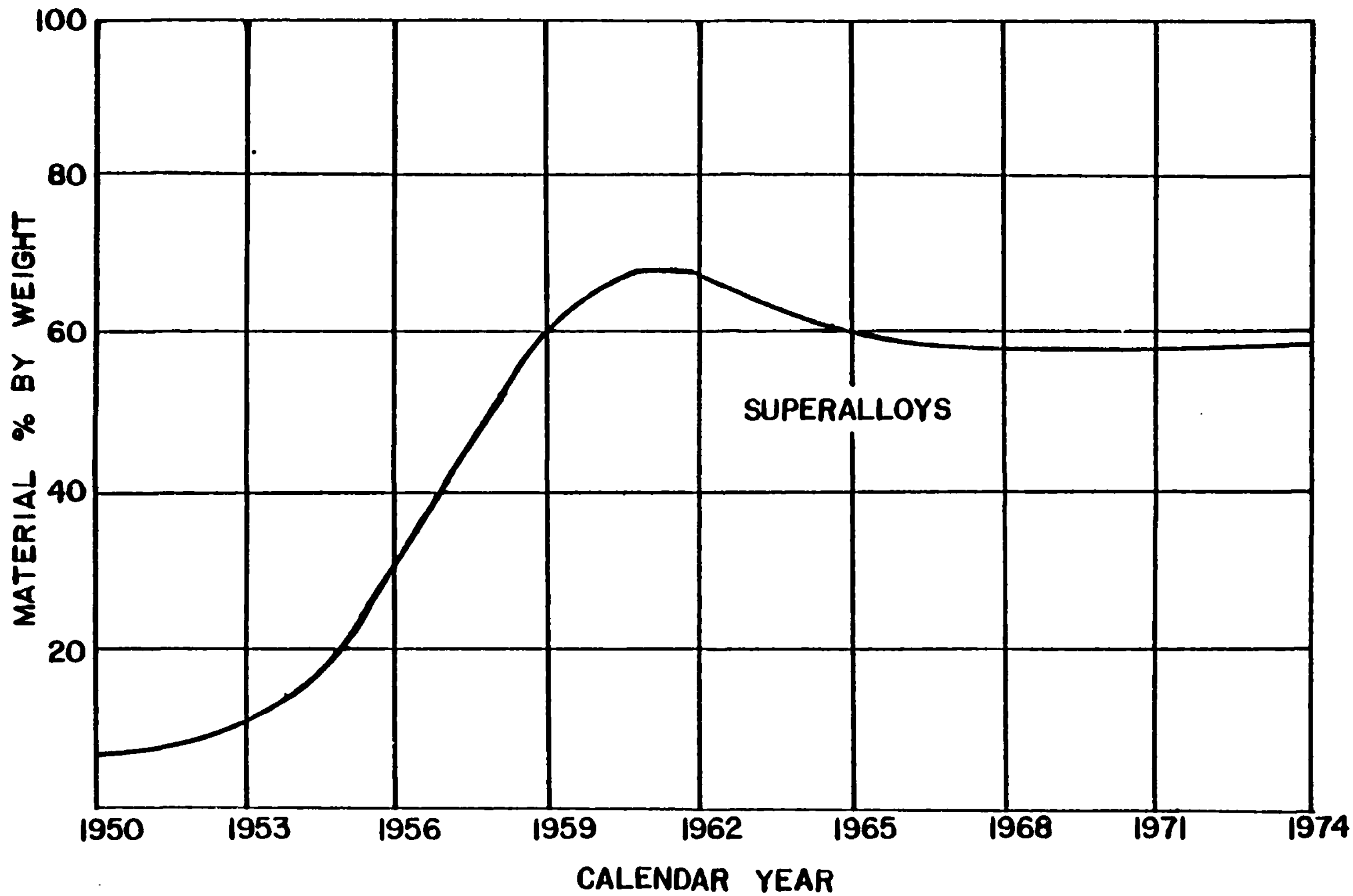

FIGURE 5 MATERIAL TRENDS

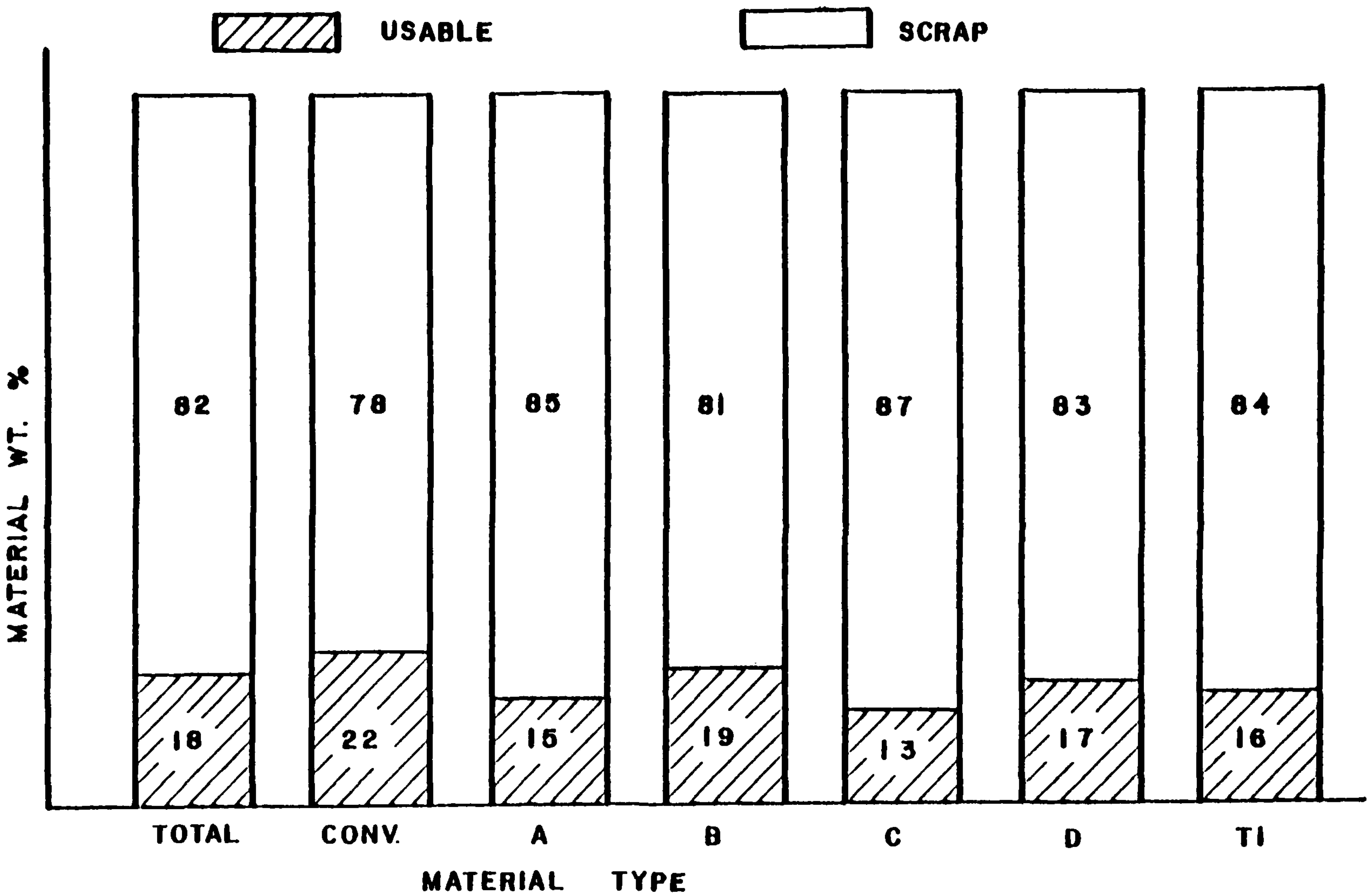

FIGURE 6 DESIGN INFLUENCES

	MAJOR CASE, DISC, SPACER SHAFT					
	TI	A	B	C	D	CONV
RELATIVE MATERIAL COST	7.0	3-4	4-5	5-7	7-10	1.0
RELATIVE MACHINING COSTS	1.5	1.9	3.1	4.0	3.5	1.0
RELATIVE WEIGHTING FACTOR	10.5	6.7	14.0	24.0	29.8	1.0
TYPICAL MATERIALS	6AL-4V 6AL-6V-2Sn	17-4PH SS A-286 GREEK ASCOLOY	HASTELLOY-X HASTELLOY-B INCO-706	L-605 INCO-718 INCO-625	WASPALLOY RENE-41 ASTROLOY	321 SS CARBON STEEL ALUMINUM

FIGURE 7 MATERIAL CLASSIFICATION

$$\text{MAURER FACTOR} = \sum_{i=1}^{n} w_i W_i$$

$$= \left(w_1 W_1 + w_2 W_2 + \ldots\ldots\ldots w_n W_n \right)$$

WHERE w_i IS THE WEIGHT OF THE ith PART &

W_i IS THE CORRESPONDING WEIGHTING FACTOR

FIGURE 8 MAURER FACTOR DERIVATION

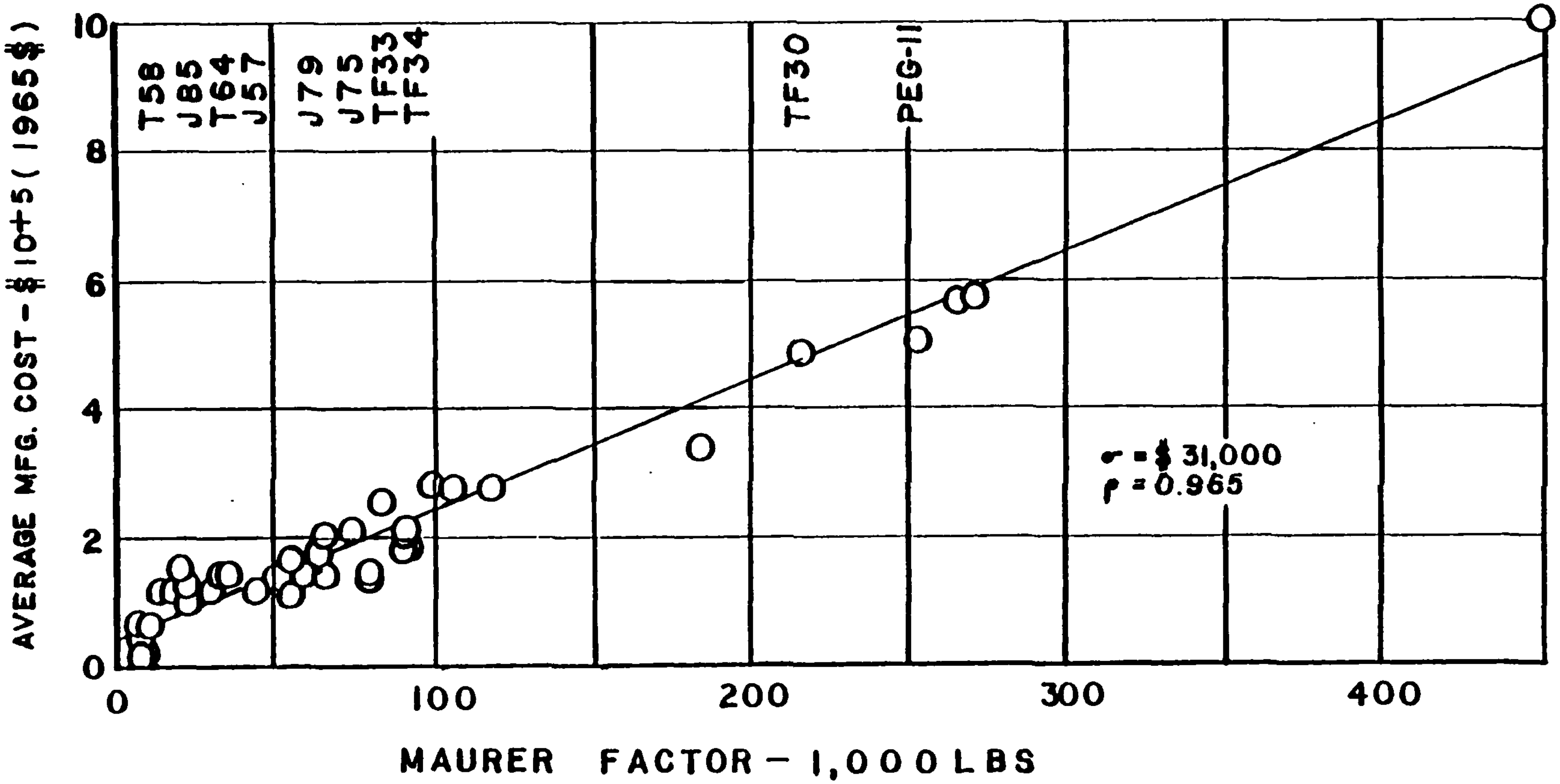

FIGURE 9 MAURER FACTOR CORRELATION WITH COST

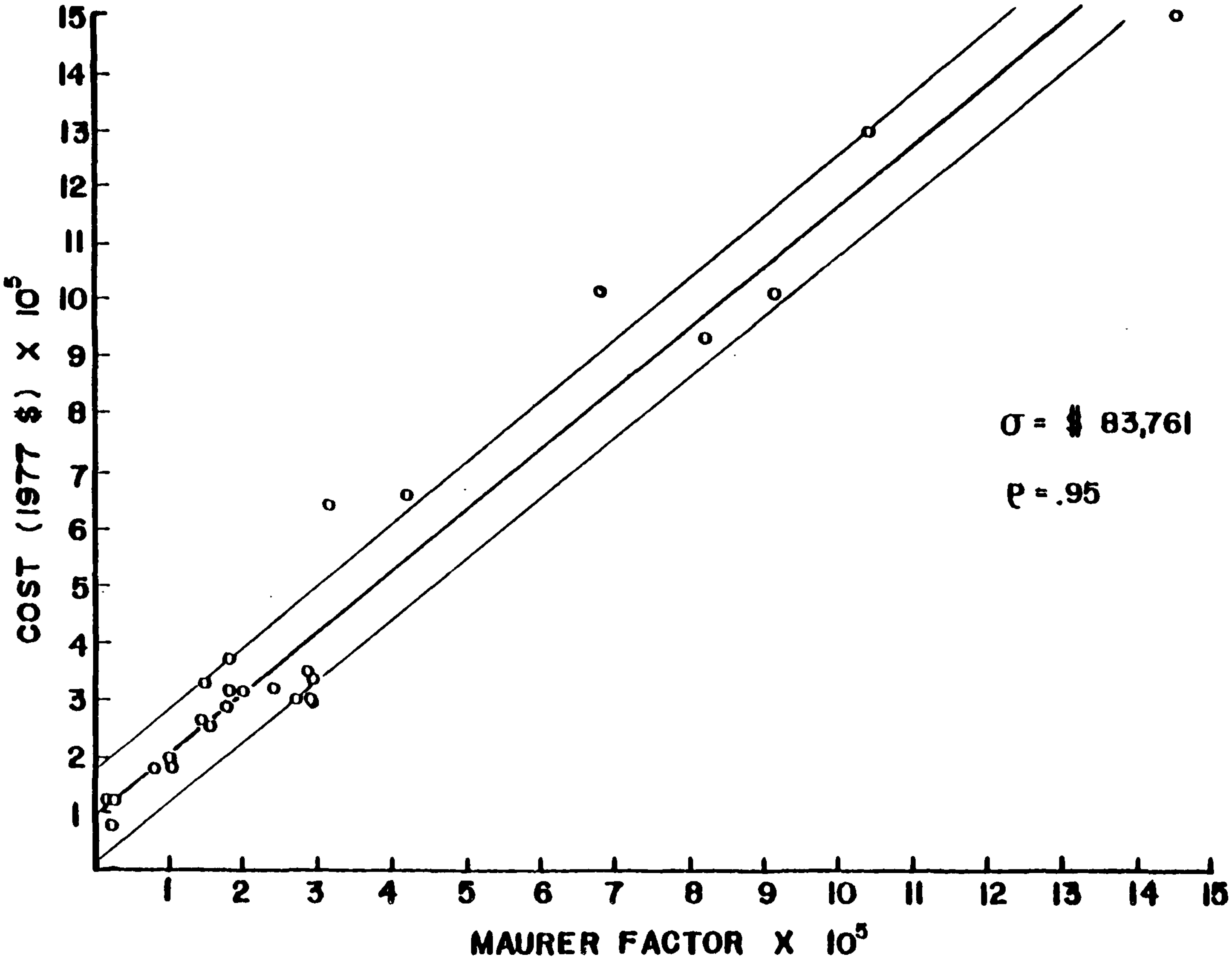

FIGURE 10 REVISED MAURER FACTOR CORRELATION WITH COST

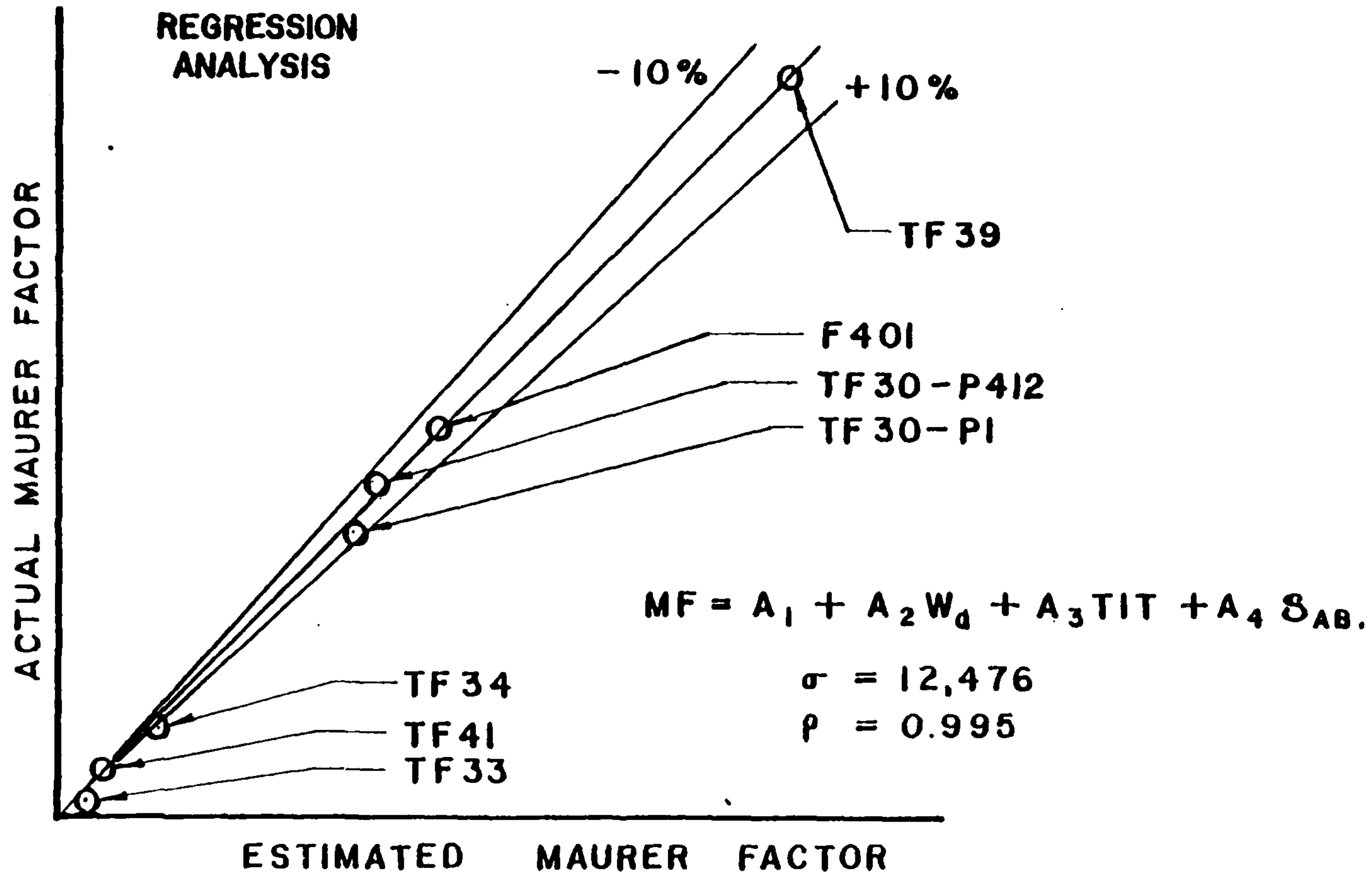

FIGURE 11 PRODUCTION ENGINE COSTING BY PARAMETERS

- TURBOFANS
- TURBOJETS
- TURBOPROPS /SHAFTS

SIGNIFICANT PARAMETERS

TIT

W_a

$\delta_{A/B}$

F_n

SHP

RANGE OF APPLICATIONS

- NEW ENGINES
- UPRATING OF CURRENT ENGINES
- SCALING OF PROPOSED ENGINES
- CYCLE / COST TRADE - OFF

FIGURE 12 CORRELATIONS

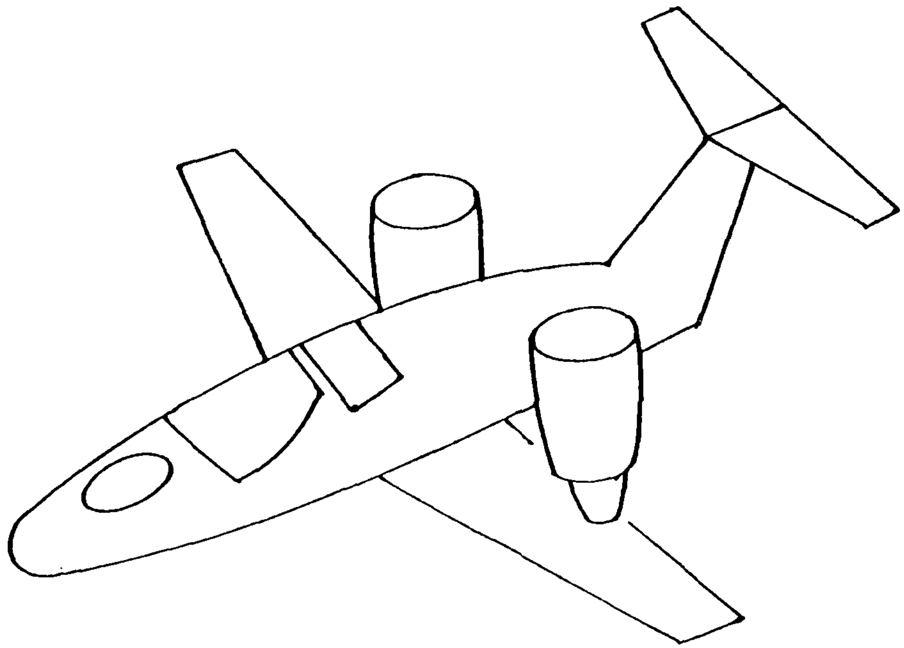

FIGURE 13 LIFT FAN ACQUISITION COST

	cards	core (octal)	type	status
Repair & Overhaul	250	50000	Accounting	Completed & Validated
Vane & Blade I	500	50000	Day-Step Probabilistic Simulation	Completed & Validated
Vane & Blade II	2000	100000	Event-Step Probabilistic Simulation	Completed & Validated
Power Plant Costing(PPC)	3000	300000	Event-Step Probabilistic Simulation	Completed
PPC OUTPUT Processor	750	175000	Report Generator	Completed

FIGURE 14 COMPUTER MODELS

TIME

- SIMULATION LENGTH
- REPORT INTERVAL
- H.S. INSPECTION
- DEPOT-BASE PIPELINE
- IMA REPAIR
- BASE-DEPOT PIPELINE
- DEPOT REPAIR DURATION
- A/C DELAY BEFORE FLYING
- ENGINE INSTALLATION
- ENGINE CANNIBALIZATION
- MAXIMUM ENGINE FH/MONTH
- MAXIMUM ENGINE LIFE (FH)
- FH BETWEEN DEPOT VISITS
- MINIMUM ENGINE OPERATION

FIGURE 15 OPERATING & SUPPORT COST PROGRAM INPUTS RELATING TO TIME

QUANTITIES

- NUMBER OF ENGINES PER A/C
- NUMBER OF DEPOT SERVERS
- RANDOM NUMBER SEED

OPERATING FACTORS

- IMA ADDITIVE REPAIR FACTOR
- A/C ATTRITION RATE
- DEPOT REVISIT TIME FRACTION
- REMAINING LIFE FRACTION TO DEPOT

FIGURE 16 OPERATING & SUPPORT COST PROGRAM INPUTS RELATING TO OPERATING FACTORS AND QUANTITIES

FAILURE TYPES

- EXPONENTIAL
- UNIFORM
- NORMAL
- LOGNORMAL
- WEIBULL
- FAILURES PER CUM FH

FIGURE 17 OPERATING & SUPPORT COST PROGRAM

AIRCRAFT STATUS

CURRENT NUMBER

- AIRCRAFT FLYING
- AIRCRAFT WAITING FOR ENGINE INSTALLATION
- AIRCRAFT UNDERGOING HOT SECTION INSPECTION
- AIRCRAFT ATTRITED (CRASHED OR RETIRED)

FIGURE 18 PROGRAM OUTPUT–OPERATING & SUPPORT COST AIRCRAFT

MAINTENANCE FACILITY STATISTICS

ENGINES REPAIRED

- AT IMA
- AT DEPOT
- BY BOTH
- PER DAY AT IMA
- PER DAY AT DEPOT

FIGURE 19 PROGRAM OUTPUT-OPERATING & SUPPORT COST
MAINTENANCE FACILITY

ENGINE STATISTICS

- REMOVALS DUE TO FAILURES
- HOT SECTION INSPECTIONS
- HOT SECTION INSPECTION DETECTIONS
- REMOVALS DUE TO MAXIMUM PART LIFE
- TOTAL TIME ALL ENGINES SPEND WAITING FOR PARTS
- CURRENT NUMBER OF RFI ENGINES

FIGURE 20 PROGRAM OUTPUT—OPERATING & SUPPORT COST ENGINES

ENGINE REMOVALS BY CAUSE

- MAXIMUM PART LIFE
- FAILURE FROM 5 CURVES
- HOT SECTION
- MAXIMUM ENGINE LIFE
- HIGH TIME DEPOT
- FOR A/C RETIREMENT

FIGURE 21 OPERATING & SUPPORT COST PROGRAM OUTPUT CAUSES

ENGINE RATIOS

- CURRENT CUMULATIVE FLIGHT HOURS ON ALL ENGINES
- INSTALLATION RATIO
- PREMATURE REMOVAL RATE
- TOTAL REMOVALS PER DAY
- MEAN FLIGHT HOURS BETWEEN REMOVALS

FIGURE 22 OPERATING & SUPPORT COST PROGRAM OUTPUT RATIOS

		BASIS
DEPOT	$106/HR	NARF DEPOT
	$49/HR LABOR	"B" REPORTS FY '76
	$57/HR MATERIAL	
BASE	$43/HR	3M 23XXX WUC ENGINE ONLY
	$29/HR LABOR	of 1.435 man hrs./flt. hour ASSUMED $30/HR.
	$14/HR MATERIAL	· $20/HR LABOR · $ 10/HR MATERIAL
TOTAL	~$150/HR	

FIGURE 23 NORMALLY REPORTED MAINTENANCE COSTS AVERAGE FOR TF30 FAMILY OF ENGINE FY 1976

		BASIS OF ESTIMATE
DEPOT		
-O.H. & REPAIR	$106/HR.	DEPOT "B" REPORT
-COMPONENT REPAIR	$ 88/HOUR	F/E FROM (A/F MISTRE COSTS)
-CONDEMNED PARTS	$200/HR.	SALES OF REPLENISHMENT SPARES PLUS ESTIMATE OF DEFERRED ITEMS & NON PWA SUPPLIED PARTS
-STANDARD STOCK ITEMS	$20/HR.	10% OF REPLENISHMENT SPARES (SSSF FUND A/F)
-MODS	$36/HR.	ESTIMATE OF KIT COST INSTALLED DURING INTERVAL
SUB TOTAL	$450/HR.	(NOTE: CIP EXCLUDED)
BASE	$106/HR. or $249/HR.	3M ALL PROPULSION SYSTEM RELATED MAINTENANCE ACTIONS @ $30/HR. MANPOWER LOADING 1 1/2 MEN PER INSTALLED ENGINE
RANGE OF TOTAL COST	$556 to 699	ROUGHLY $600/HR./ENGINE

FIGURE 24 TF30 TOTAL MAINTENANCE COSTS

- COSTS FOR OVERHAUL AND REPAIR AVAILABLE SINCE FY 1967 to DATE
- MODULE/COMPONENT REPAIR & OVERHAUL COSTS AVAILABLE FOR 3-4 YEARS
- DETERMINATION OF MAJOR COST DRIVERS IN DEPOT MAINTENANCE WILL BE POSSIBLE
- COLLECTION & ANALYSIS WILL REQUIRE SUBSTANTIAL EFFORT
    - NUMBER OF TYPES OF RECORDS
    - VOLUME OF DATA

FIGURE 25 NAVY NARF COST DATA STATUS

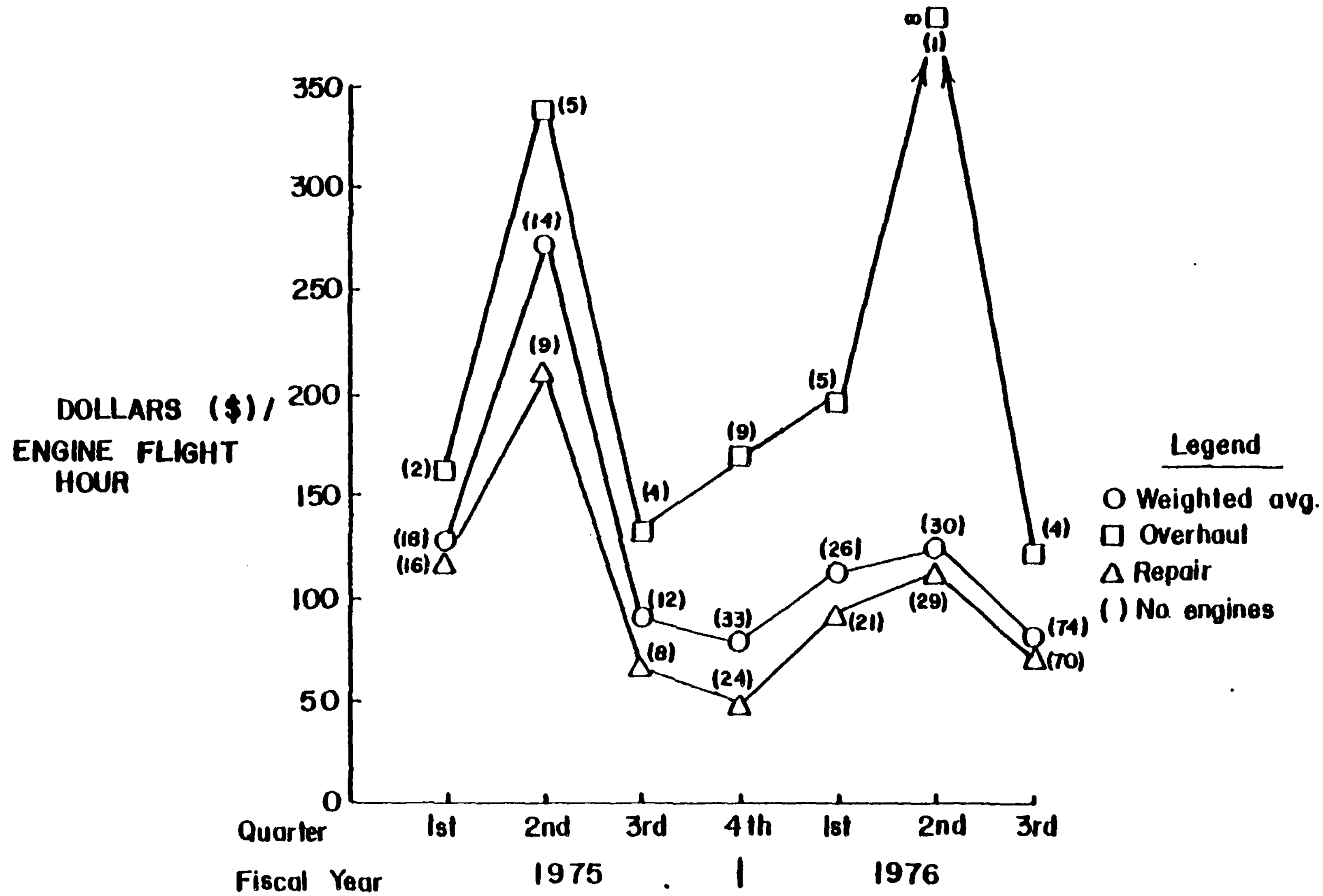

FIGURE 26 TF30-P-412 DEPOT MAINTENANCE COST LABOR COST/ENGINE FLIGHT HOUR

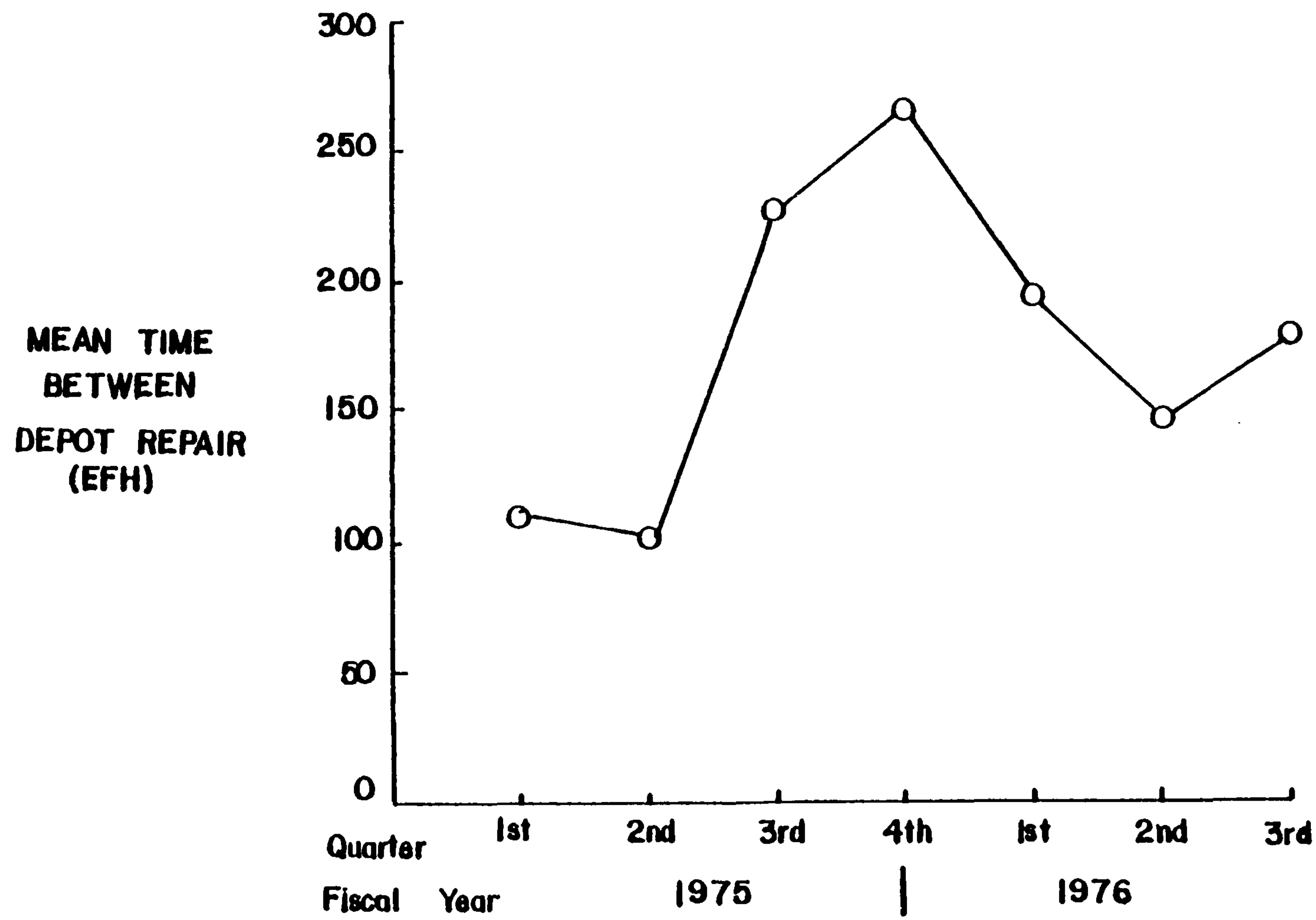

FIGURE 27 TF30-P-412 MEAN TIME BETWEEN DEPOT REPAIR

TASK 1	Determine the level and the trend with time from IOC of maintenance cost at whole engine level
TASK 2	Determine the distribution of such costs at the module and component level and cost drivers
TASK 3	Develop a cost estimating relationship for predicting engine maintenance cost from module and component design parameter
TASK 4	Recommend changes to design and/or maintenance practices to reduce L.C.C. and define economic benefit
TASK 5	Identify and document necessary changes to navy data collection system and new data required to provide for effective technical cost monitoring & control

FIGURE 28 PROPOSED MAINTENANCE COST STUDY PROGRAM

ESTIMATING THE MANUFACTURING COST OF SMALL TURBOSHAFT ENGINES

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Introduction

Several methods have become available for estimating the cost of turbojet and turboshaft aircraft engines. In most instances, the cost expression is related to a performance parameter, such as shaft horsepower (SHP) or thrust (T). The dollar value of the historical data is normally based on the price paid for by the Government for each engine, and finally, the price quoted per unit is not relatable to the production quantity or production rate which may have varied with each fiscal year, or even quarter.

With the increased emphasis being placed on the application of the design-to-cost (DTC) philosophy and on the implementation of design-to-unit-production cost (DTUPC) in DOD contracts, this Laboratory initiated a study effort of the many cost estimating methods available to determine which method would prove best for estimating the manufacturing cost of turboshaft engines designed for current and future US Army helicopters.

The US Navy developed Maurer Factor (MF) (Reference 1) and the Detroit Diesel Allison (DDA) developed Materials Index Factor (MIF) (Reference 2) were analyzed in regard to their applicability for making an independent Government cost estimate of advanced technology turboshaft engines. The Maurer Factor method was chosen because of US Navy support in evaluating engine designs. As a result of this evaluation, this Laboratory established a Material Index Factor (MIF) methodology utilizing the best features of these methods. This methodology has been verified with new US Army data.

Discussion

Several methods have been developed for estimating the manufacturing cost of turbine engines. The most widely used method within the US Army is the Cost Estimating Relationship (CER) which was derived from historical data and which is based on the intermediate rated shaft horsepower of similar gas turbine engines. This method is considered adequate as a first estimate of the price of a turbine engine of a certain power output. Even though the CER implies cost, the historical data available to the US Army are based on the average price paid by the Army for each engine lot;

therefore, the manufacturing cost estimate of a new design is only a rough estimate since G&A and Profit rates are assumed. The CER method is adequate for estimating the engine cost of a new helicopter under consideration where total Flyaway Cost and Life Cycle Cost (LCC) must be determined. The analyst must remember though, as well as explain in his report, that the cost (price) determined for the engine in the LCC analysis was derived from data of past and only a very few current technology engines; therefore, cost savings or cost increases due to technological advances in materials and internal aerodynamics are not included.

The CER equation for the average price of the first 100 production engines of less than 900 SHP is expressed as:

$$\$74 = 2.697079\ (SHP)^{1.571261} \times 1.0011 \qquad (1)$$

A parametric method developed at the Institute for Defense Analysis (IDA) defines manufacturing cost as a function of shaft horsepower. This method is also explained in Reference 4. The equation developed calculates the cumulative average recurring price at 1,000 units and is expressed as:

$$\$74 = \left[3\ (SHP)^{1/3} + 0.03\ (SHP)\right] \times 1000 \qquad (2)$$

The most accurate engine cost estimate available today still is the Industrial Engineering estimate. This estimating procedure is normally beyond the capabilities of the Government cost analyst since a detailed knowledge of the work processes and materials is required for each design as well as the manufacturing efficiency of each contractor.

The method of cost estimation which will be discussed in greater detail is the Material Index Factor (MIF) or Maurer Factor (MF). Both of these methods are explained in detail in Reference 1 and Reference 2 and, therefore, will not be discussed except for some pertinent points. The Maurer Factor (MF) method was used by this Laboratory to evaluate the proposed manufacturing cost of the 100th production engine designs of an advanced technology demonstrator engine of approximately 800 SHP each. In addition to furnishing all the required details necessary for a thorough evaluation of the technical merits, each offeror was requested to supply the Material Monitoring List (MML) which delineates the materials that will be used by the offeror in the design of the engine. This list was also developed by the US Navy to support the Maurer Factor analysis of engine cost. Finally, each offeror was requested to provide a rationale and a substantiation of the learning curve used as well as any other information necessary so that the price or the cost of each engine could be computed and verified.

The engine cost computation was conducted using the US Navy developed equation for small ($\leq$ 1000 SHP) turboshaft engines. The manufacturing cost is expressed in 1965 dollars and represents the average manufacturing cost of 1500 engines.

$$\$65 = 4.452\ (MIF) + 3{,}582 \qquad (3)$$

The Material Index Factor (MIF) is computed as follows:

$$MIF = \sum \omega_n W_n \text{ where} \qquad (4)$$

ω = relative weighing factor

W = material input weight

In order to establish a frame of reference, a third equation was used to arrive at an approximate manufacturing cost prior to having knowledge of the material usage by the manufacturer on any of the proposed designs. The US Navy developed relationship which was originally derived based on knowledge of turbine inlet temperature and air flow rates was expressed as an approximation of the MIF weight.

$$MIF = 10.51\ (SHP) - 6155$$

As can be seen from Figure 1, this equation underestimates the actual MIF values by a considerable amount, in fact by over 50%.

At the beginning of the evaluation, the following cost figures were available for consideration and which could be compared with the offeror's proposed manufacturing costs of the 100th production unit:

Method	1976 Dollars
CER	78,366.00
IDA	58,629.00
MIF (SHP)	36,617.00

Of the three cost estimates shown, it was believed that the CER estimate would be the most realistic value and that the offeror's design-to-unit production cost (DTUPC) quote should be within a reasonable percentage of that estimate.

The Government evaluation was conducted in accordance with the US Navy established equations (3) and (4). Each offeror proposed a learning curve of 90% or nearly that value. Some of them provided an extensive list of vendor purchased items and the MIF or cost was computed as follows:

1. The MIF weight was calculated based on the input weight and classification of the materials used.

2. Using this MIF weight, the 100th production unit cost was calculated, inflated to 1976 dollars.

3. The price was calculated by applying the rates of G&A, IR&D and Profit.

4. To this price, the vendor price of the accessories and controls were added, and this total price was compared to the proposer's 100th production unit price.

5. In order to arrive at an adjusted MIF value, the 100th production unit cost was calculated in 1965 dollars and, by using the appropriate learning curve to compute the average cost of 1500 engines, equation (3) yielded the adjusted MIF value.

The results of the first cut evaluation are shown in Figure 1, and as can be seen from this figure, discrepancies were evident between the proposers' quotes versus the Government estimate. It was learned from some of the offeror's that they had included consideration for experience and learning from a similar engine which would have been in quantity production for several years by the time of production of this new design engine. After removing the "pre-load," the offeror's quote was closer to the Government's estimate. (Pre-load is discussed below.) Similarly, another offeror whose quote was much below the Government estimate, was asked to review the Monitoring Material List (MML) supplied. It appears that a mistake was made in the material specification cost part. The corrected specification reduced the MIF. As a result, the Government cost estimate was also reduced. In general, removing the "pre-load" resulted in a proposed (adjusted) cost which was within 8% of the Government's estimate.

The method used to account for learning (pre-load) was to compute the actual cost of similar items. For example, it is assumed that the proposed 100th production unit cost of a new design engine is $45,000, in 1976 dollars. Forty of 56 parts of the new design are similar to parts of an older, known design and the proposed cost of these 40 parts is $30,000, in 1976 dollars. The $15,000 remaining constitutes the cost of the new items of the proposed design. Three-thousand units of the older engine would have been produced by the time of production of the 100th unit of the new design. The older engine was documented to have an 89% learning curve.

The data point of $30,000 at unit 3,000 on the 89% learning curve can be used to determine the cost of the 40 parts at the 100th unit, which is $54,000. (Figure 2) The $54,000 would be the cost of the 40 parts of the new design engine if the offeror had not taken credit for experience with the older engine. Therefore, the adjusted proposed cost would be $54,000 + $15,000 = $69,000. This adjusted cost should be close of the Government estimate.

Following the evaluation, the MIF methodology was reevaluated and some adjustment to the basic equation was found to be necessary since the regression line computed from the 13 data points shown in Figure 1 did not give the values used in equation (1). In addition, it was decided to drop the second highest cost engine data point because of the excessive deviation from the line. As a result, a new equation was generated for a MIF analysis of small turboshaft engine manufacturing cost and the regression line, which is based on historical data, and the equation is shown in Figure 3. For the purpose of comparing the evaluation results with the new equation, the appropriate inflation factor was applied and

the manufacturing cost of the 100th production unit of the MIF equation is shown together with the data points from the evaluation. The cost values and the corresponding MIF weights were adjusted to preclude release of proprietary information. It is evident that excellent agreement exists for four of the five designs evaluated.

Because of that disagreement, a detailed study of the various metals used by each proposer was made. Examples of material usage for this size engine, expressed in percent input weight, are shown in Figure 4. As can be seen, one offeror used the highest percentage of conventional materials, such as steel and aluminum. A detailed analysis of the Material Monitoring List indicated that this offeror also had the highest input to output ratio, that is, the highest input weight to finished weight ratio. This tends to imply that he has a high material scrap rate.

Conclusions

As a result of this study, it is believed that this MIF method appears to be the most effective if not the most accurate method available to date to the Government cost analyst for estimating the production cost of a turboshaft engine. In addition to being able to accurately estimate the production cost of these engines, the MIF method can be used by the Government to track the DTUPC of the engine as early as during the advanced development phase. There is strong evidence that the method is useful in determining the efficiency of a design and that it appears to be a useful tool for identifying cost reduction candidates of components and items on turbine engines. Also, the MIF method compensates for advancements in engine technology, that is, increased use of high temperature (high cost) alloys is automatically considered in the computation of the MIF weight. And finally, engines of the same shaft horsepower but designed by different companies will have different MIF's.

Other Uses

It is believed possible that the MIF method could prove useful in estimating the manufacturing cost of nonengine related items. Following the work on engine cost, a need arose to quickly estimate the manufacturing cost of a rotor hub of a large helicopter. Cost data from US Army sources could not be used because the data available was from the replacement cost of the assembled, ready to install rotor hub which includes bearings, links, etc. It was learned that the hub housing consists of a 4340 steel forging with an input weight of 790 pounds. Machining of this hub requires 77 operations and results in a waste rate in excess of 80%.

The relative weighing factor of 4340 steel forging was assumed to be 1.0, to be in consonance with the US Navy classification. Use of the new small turbine equations resulted in an estimate of the 500th production unit price of $8,985.00. This estimate compares with the quoted price of $10,100.00 for the hub housing.

Potential Further Application

On the basis of the good correlation obtained between the manufacturing costs predicted by the Material Index Factor and those proposed by each

of the offerors during the 800 SHP ATDE competition, it is concluded that the Material Index Factor is a good tool for use in predicting the manufacturing cost of small, advanced technology turboshaft engines. It is anticipated, therefore, that the Material Index Factor will be updated periodically during the course of the 800 SHP ATDE program and used as a tool in tracking the design-to-unit production cost effort in addition to being used as a tool to evaluate candidate cost reduction efforts. It is also anticipated that this tool will be used by the Army in the evaluation of proposals for any future engine demonstration or development efforts.

It should be noted once again that the good correlation obtained during the evaluation was for small (less than 1000 SHP) turboshaft engines. It is felt that further studies should be undertaken to verify the capability of the Material Index Factor in the 1000-5000 SHP class and to determine the appropriate slope and intercept for the regression equation in this area. This effort would consist primarily of collecting the required engine cost data and the material input weights for engines in this horsepower class.

The success obtained with the Material Index Factor in predicting the cost of a helicopter rotor head is of considerable interest. If the method works well for engines and rotor heads, there is reason to believe that it can also be applied to helicopter drive systems. In order to accomplish this, there are two major tasks to be performed. First, relative weighting factors must be established for the materials and machining processes which are used in helicopter drive trains, gears, bearings, shafting, casing, etc. These materials and processes are, for the most part, different from those used in the manufacturing of engines. Second, a base of historical data must be collected to determine the slope and intercept of the cost versus Material Index Factor regression line. Of the two tasks, the second is expected to be the more difficult. Drive trains are not procured by the Army in the same manner as engines. Engines are normally procured as an end item by the Government and subsequently furnished to the airframe manufacturer. Drive train components on the other hand, are obtained as part of a total aircraft system and, as a result, little or no historical data exists within the Army relative to drive train production costs.

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2. L. L. Robinson, B. A. Zolezzi and D. K. Hanink, MATERIALS INDEX FACTOR METHODS FOR ESTIMATING MANUFACTURING COST OF ADVANCED POWER PLANTS, Paper presented at the Aircraft Engine Design and Life Cycle Cost Seminar, Naval Air Development Center, Warminster, PA, November 1975.

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CER

$$\$_{74} = 2.697079\,(SHP)^{1.571261} \times 1.0011 \qquad (1)$$

IDA

$$\$_{74} = \left[3\,(SHP)^{1/3} + 0.03\,(SHP) \right] \times 1000 \qquad (2)$$

FIRST ESTIMATE, 100th PRODUCTION UNIT

METHOD	1976 DOLLARS
CER	78,366
IDA	58,629
$MIF_{(SHP)}$	36,617

$$\left[\ MIF = 10.51\ (SHP) - 6155\ \right]$$

Material Index Factor (MIF)

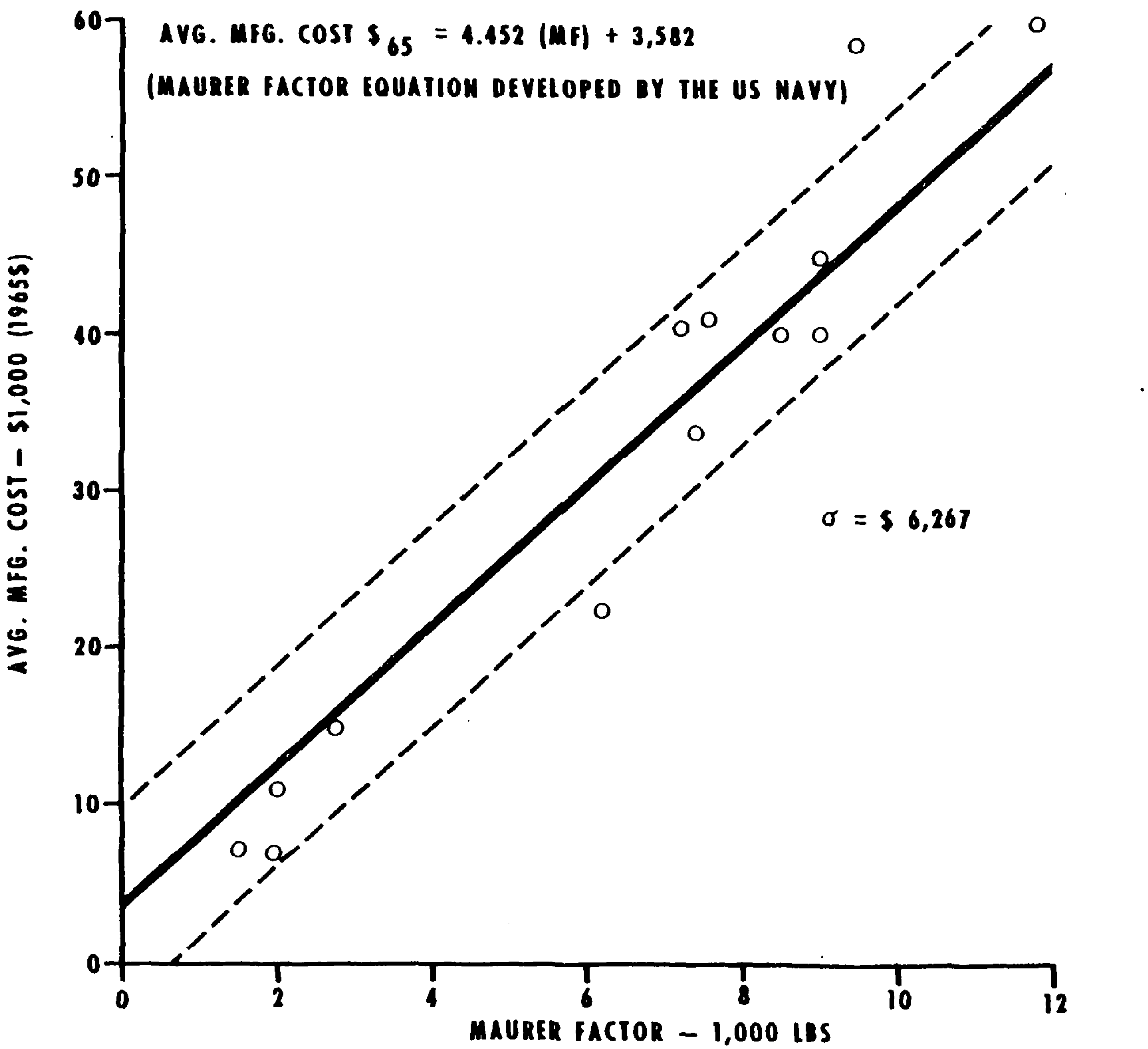
$$\$_{65} = 4.452\,(MIF) + 3.582 \tag{3}$$

$$MIF = \sum \omega_n W_n \tag{4}$$

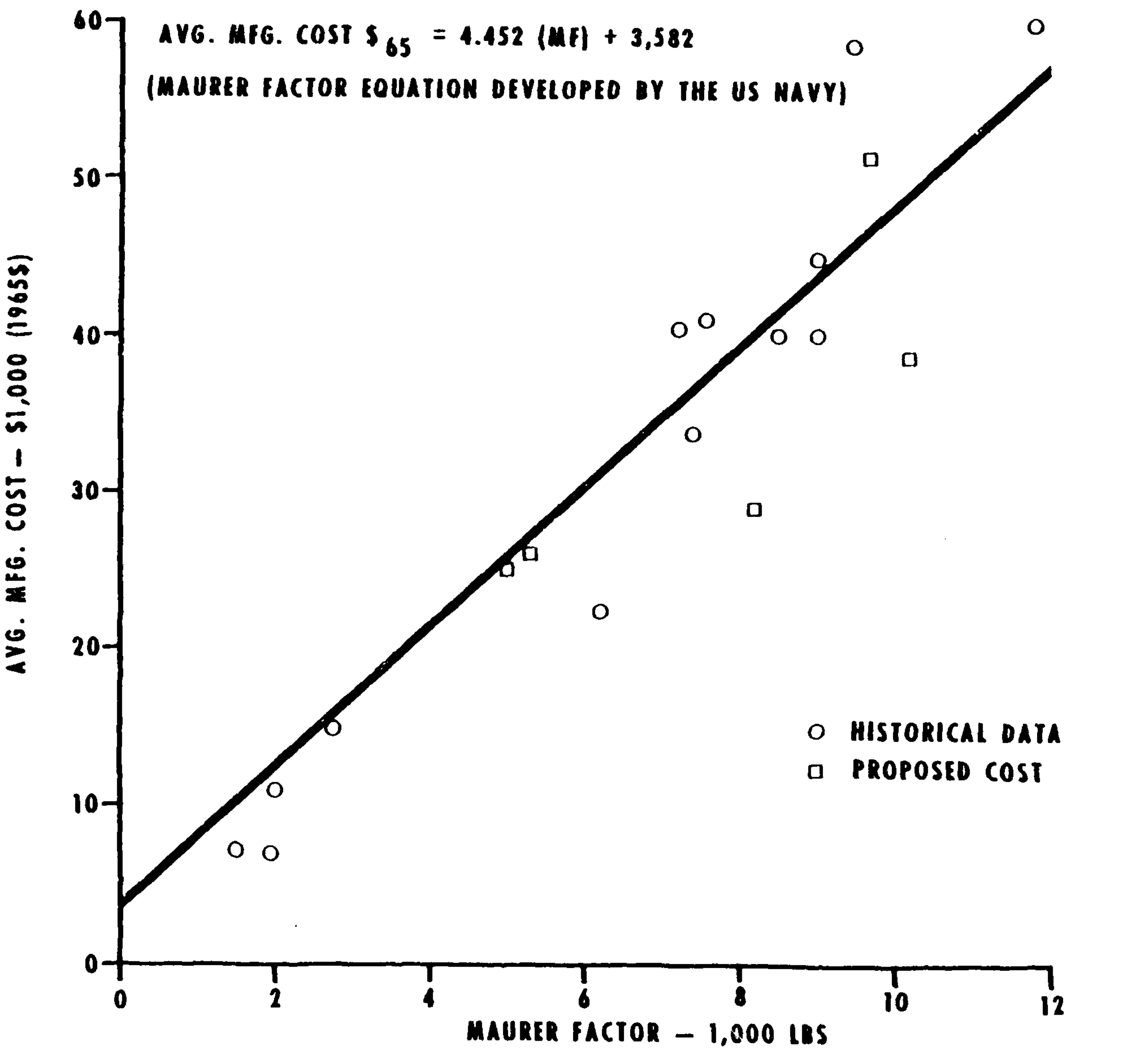
ω = relative weighing factor

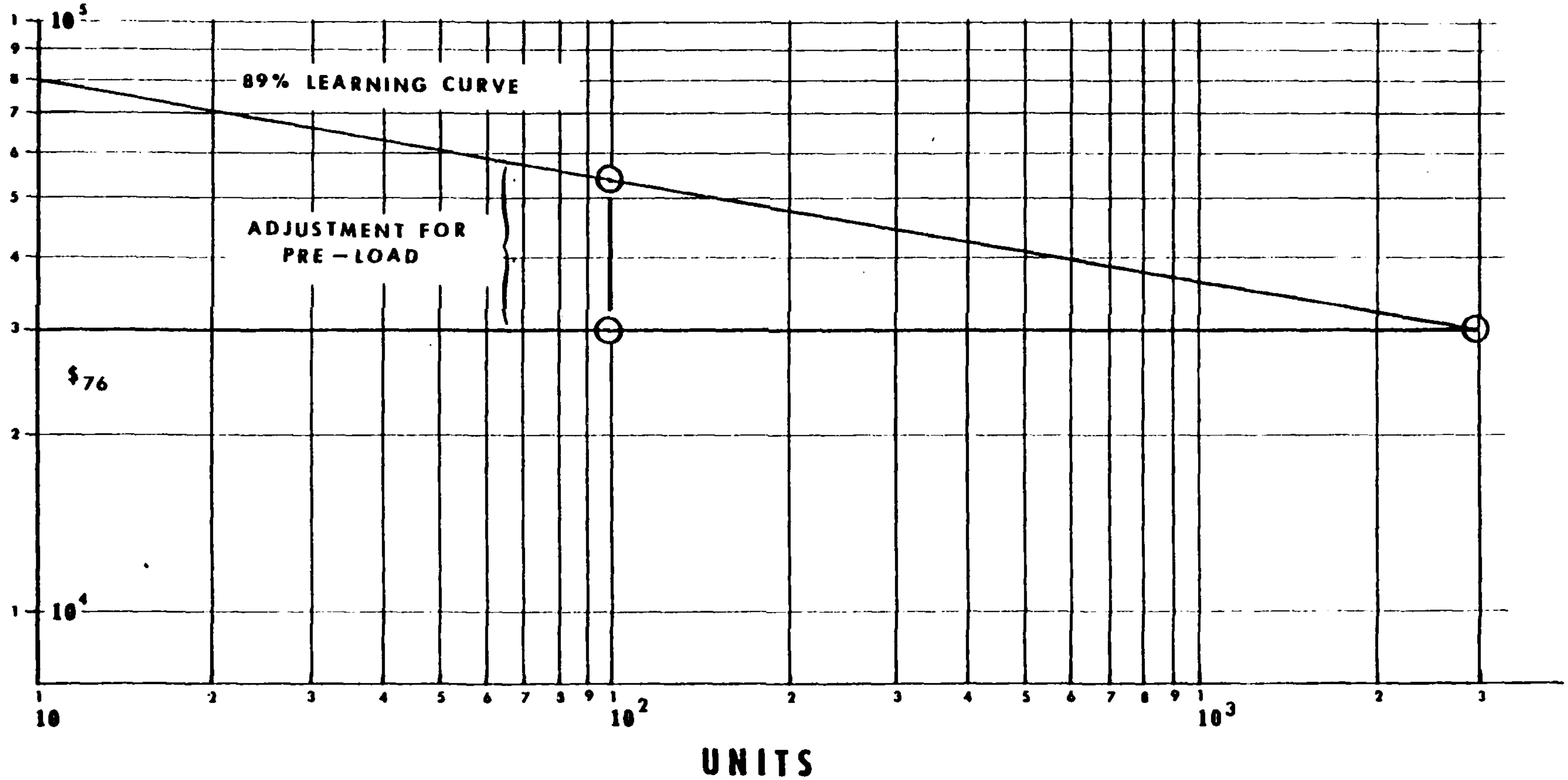
W = material input weight

MAURER FACTOR CORRELATION WITH COST FOR SMALL ENGINES

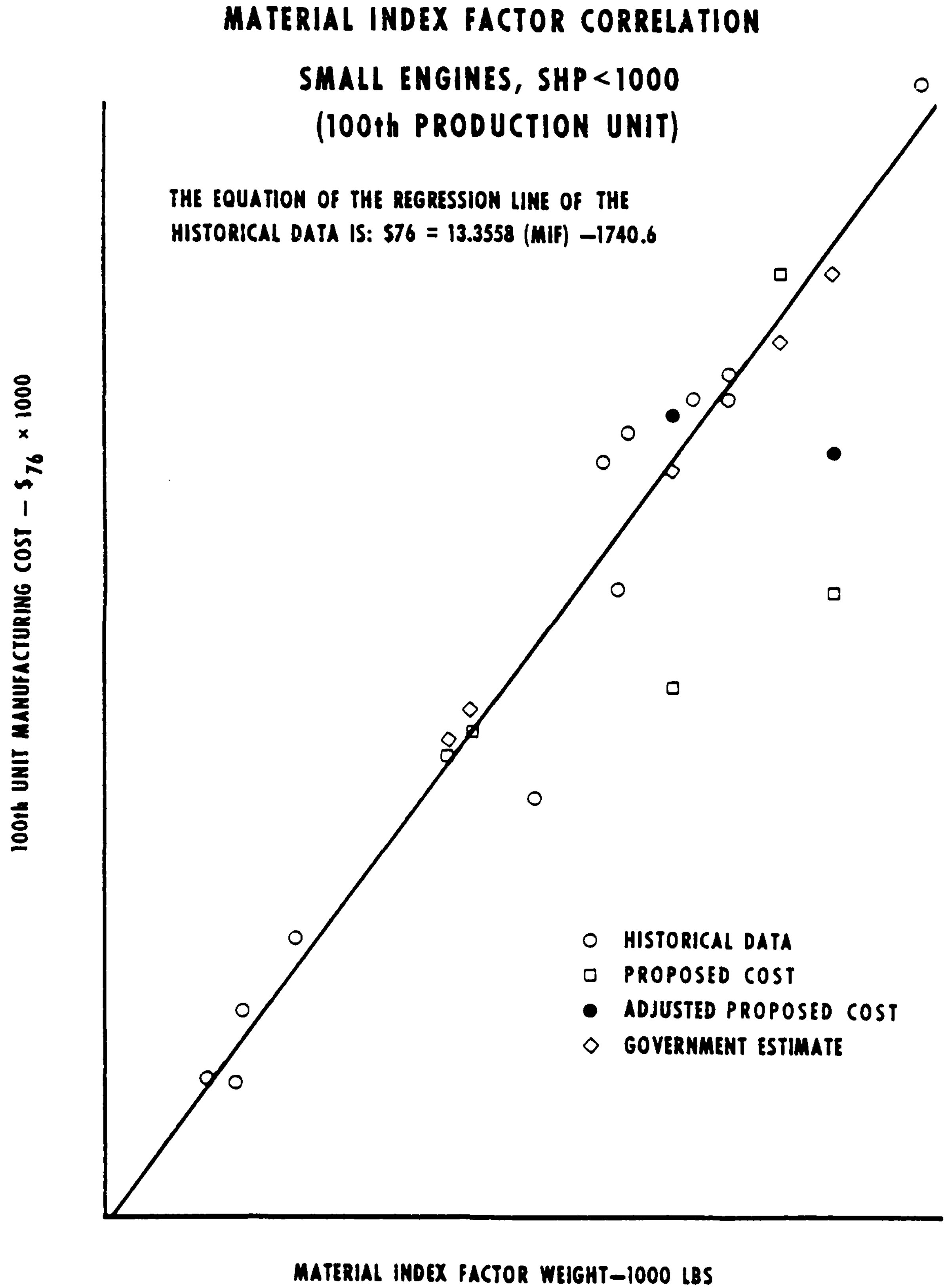


MAURER FACTOR CORRELATION WITH COST FOR SMALL ENGINES

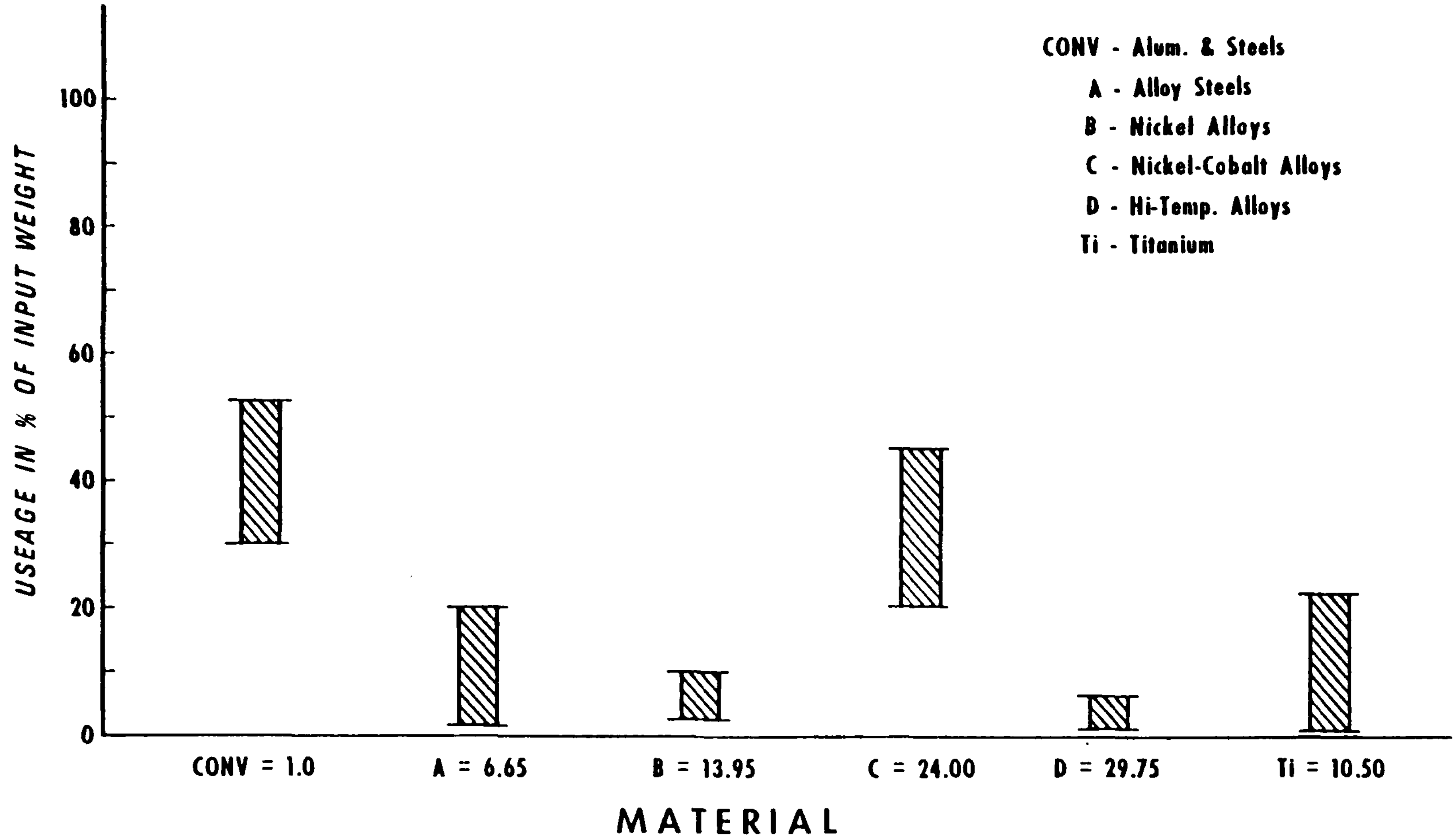




Pre-load adjustment


MATERIAL INDEX FACTOR CORRELATION
SMALL ENGINES, SHP<1000
(100th PRODUCTION UNIT)
THE EQUATION OF THE REGRESSION LINE OF THE HISTORICAL DATA IS: $76 = 13.3558 (MIF) —1740.6
100th UNIT MANUFACTURING COST — $76 × 1000
HISTORICAL DATA
PROPOSED COST
ADJUSTED PROPOSED COST
GOVERNMENT ESTIMATE
MATERIAL INDEX FACTOR WEIGHT—1000 LBS

MATERIAL USEAGE IN % INPUT WEIGHT



CONCLUSIONS

- **ENGINES OF SAME SHP WILL HAVE DIFFERENT MIF VALUES**
- **THE MIF METHOD**
  - IS AN ACCURATE AND EFFECTIVE COST ESTIMATING METHOD
  - CAN BE USED TO TRACK DTUPC
  - CAN IDENTIFY COST REDUCTION CANDIDATES
  - COMPENSATES FOR ADVANCEMENTS IN ENGINE TECHNOLOGY

ENGINE SUPPORT COST

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Background

Life cycle cost (LCC) analysis has been a part of the engine design process for several years now. This analysis has been vital in optimizing engine designs to minimize overall aircraft system LCC. Since total engine-related cost is largely unknown, it is fortunate that such optimizing can be done with reasonable confidence by calculation of cost differences only, without an intimate knowledge of total LCC. Although this analysis by differences works well in design optimization, it is not satisfactory for use by the military in engine source selection. And in dealing with possible airline-type support cost warranties, it is totally inadequate. For these considerations, good visibility into all the elements of LCC is required.

Cost Magnitude

Engine-related LCC is substantial and, in large part, unknown. In the typical fighter aircraft case shown in figure 1, 35% of the total aircraft system LCC is engine related. Engine design features heavily influence the 12% fuel portion also, and have a substantial effect on the airframe cost through their influence on airframe weight.

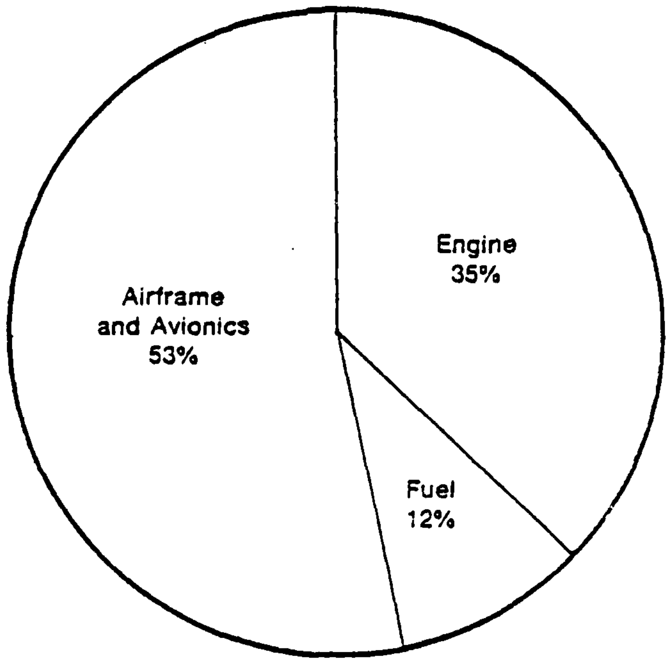

Figure 1. Engine Life Cycle Cost Is a Major Element of Aircraft System Life Cycle Cost

A breakdown of the 35% engine portion of total aircraft LCC is shown in figure 2. In the engine selection process the Navy or Air Force can project the 20% development cost portion with reasonable accuracy and can even get a firm commitment on at least that amount to be expended prior to qualification. The 30% acquisition cost portion also can be predicted within reasonable bounds. But that large support cost segment, making up one half of engine cost-of-ownership and almost 20% of total weapon system cost-of-ownership, is largely unknown.

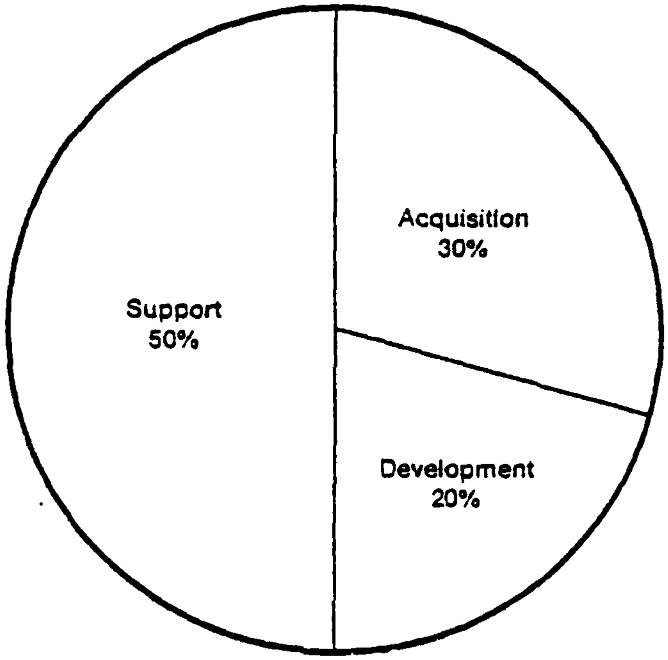

Figure 2. Support Cost Is a Major Element of Engine Life Cycle Cost

Cost Uncertainty

As illustrated in figure 3, just the *tolerance* on support cost is larger than the total of development or acquisition cost. This support cost uncertainty that exists at the time of engine source selection is not alleviated after the engine reaches operational status. Current military data systems are not producing engine data that is relatable to engine faults. Indeed, the lack of knowledge about *current* engine support cost is the reason that advanced engine support costs are not predictable.

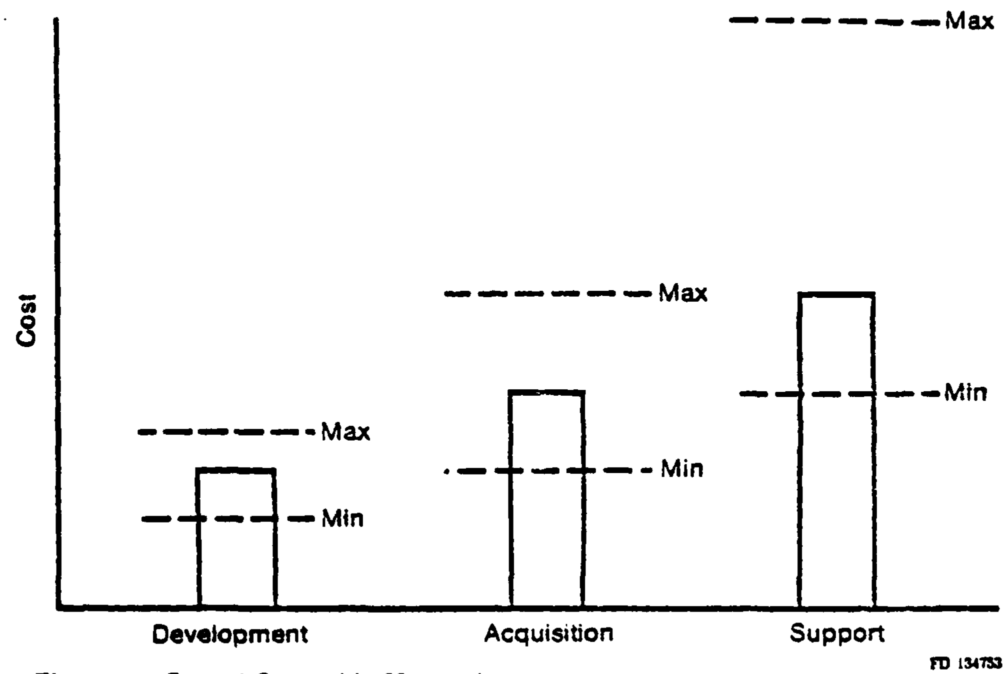

Figure 3. Cost of Ownership Uncertainty

Cost Prediction Problem

This is not to say that engine LCC models do not include formulas for predicting support cost. They do, but the support cost sections of existing LCC models help very little. In fact the simplicity and obvious mathematical correctness of the "accounting"-type model can cause us to be deluded. An actual equation set from such a model is:

C_3 = Off-Equipment Maintenance

$$= \sum_{i=1}^{N} \frac{(TFFH)(QPA_i)(UF_i)(1\text{-}RIP_i)}{MTBF_i} \Big\{ (BCMH_i)(BLR) \qquad (1)$$

$$+RTS_i[(BMH_i)(BLR + BMR) + (BMC_i)(UC_i)]$$

$$+ NRTS_i[(DMH_i)(DLR + DMR) + (DMC_i)(UC_i)]$$

$$+ [2(NRTS_i) + COND_i][(PSC)(1\text{-}OS) + (PSO)(OS)](1.35\ W_i) \Big\}$$

$$+ \frac{(TFFH)(EPA)(1\text{-}ERTS)}{CMRI}(ECH)(EUC)$$

A simplified version for illustrative purposes follows:

- $\frac{1}{MTBF} \times \frac{MMH}{Repair} \times \frac{\$}{MMH} = \frac{\text{Labor Cost}}{EFH}$ (2)
- $\frac{1}{MTBF} \times \frac{\text{Parts Cost}}{Repair} = \frac{\text{Material Cost}}{EFH}$

Certainly these equations are correct. However, they can be misleading for several interrelated reasons, not the least of which is a high sensitivity to inaccuracy of inputs which are very difficult to accurately predict. Using the hypothetical case shown in figure 4 as an example, note that the mean time between failure (MTBF) of the 6 part component is 100 hr. The component parts, A through F, vary from 250 to 20,000 hr MTBF. Their man-hours-to-repair vary from 1 to 1000 hr. Such a variation in MTBF's and repair times is not unusual among parts in a component, or components in an engine.

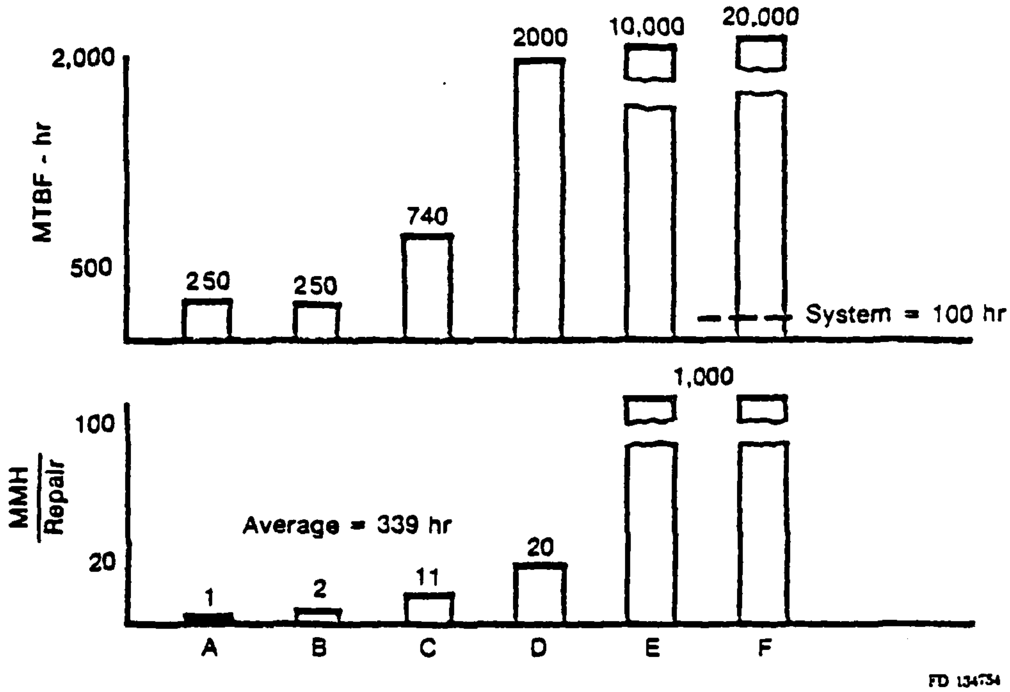

Figure 4. Average of Large Variation Means Little

Entering these values into equation 2 at the part level would produce a cost per flight hour (FH) of \$3.74. However, such equations are usually entered at the component level. Then the component MTBF of 100 hr and the arithmetic average of repair times of 339 hr would produce a cost per FH of \$6.77, high by 81%. The proper weighted average of part repair times cannot be figured without the individual part MTBF's. The significance is that such an equation cannot be effective unless entered at the basic part level and such insight is not available during source selection. In fact, it is scarcely available for currently operational engines.

Sensitivity of these equations can be further illustrated by considering possible MTBF inaccuracy. Assume that a weighted average of repair times is accurately known but MTBF of the component is missed by 1%. This would appear to distort the result by only 1%. However, the 1% error could have a greater impact on the answer. For example, if the MTBF of item E of the component described in figure 4 were missed by 50% on the low side then the overall MTBF would have been missed by 1 hr, or 1%. Instead of 100, the overall MTBF would have come out 99 and that is not far off. However, this item happens to account for over half of the maintenance manhours (MMH). Our 1% MTBF error amounts to \$2 per hour or 53% of the total cost. What we have seen is that this approach is highly sensitive to MTBF estimates. At the same time, MTBF estimates are highly subject to error, due to the same lack of data that causes support cost to be unknown.

This is an inherent problem with this approach to support cost prediction. Another weakness relating directly to this bas . approach is that the critical estimates (MTBF) must be made outside the model and provided as inputs. The model is an adding format.

Prediction Possibilities

A more useful tool for predicting engine support costs would be a Cost Estimating Relationship (CER)-type model. This approach would relate operational engine design characteristics and duty cycles to actual support costs. The observed empirical relationships would then allow prediction of advanced engine support costs as a function of information available at the time of source selection. It would depend totally on clearly observable characteristics of each competing design plus a duty cycle common to all designs. Nothing would depend on the estimates or assumptions of the contractors.

Data Problem

Unfortunately, this approach too, has a major obstacle. To be made sufficiently sensitive this model must be based on support cost data which relates directly to engine faults. Such data is not readily available. This is not to say that support cost data is not available. It is available in abundance, and some of it is accurate. However, current data systems were not intended to provide such engine fault-related visibility as is needed. Extensive investigations have been made into presently available data and inaccuracies found. It is easy to dwell on these inaccuracies as constituting the basic problem although even accurate data as presently gathered and reported is not adequate without extensive analysis.

It can be proven with Navy data, for example, that a typical fighter engine is being maintained for $150 per engine FH. Table 1 shows a breakdown of this cost and indicates sources of the data.

Table 1. Engine Maintenance Cost Normally Reported — Typical Fighter Engine

	Cost	*Basis of Estimate*
Depot		
Labor	$ 49/FH	Production performance
Material	57/FH	report, Section B
Total	$106/FH	("B" Report)
Base		
Labor	$ 29/FH	3M 23XXX Work unit codes
Material	14/FH	only: 1.435 MMH/EFH
Total	$ 43/FH	assumed $30/MMH $20/MMH labor $10/MMH material
Total Cost	~$150/FH	

These numbers were actually believed, before Navair and NADC initiated support cost research activity during the past 2 years. Those "B" reports were taken to be the total depot expenditure. The base labor cost of $29 per FH is the product of 1.435 MMH/FH from the 3M system and a labor rate of $20 per MMH. The material cost assumes $10 per MMH. Not unreasonable at all, however, table 2 indicates that some costs had been overlooked.

Table 2. Engine Maintenance Cost Estimate — Typical Fighter Engine

	Cost	Basis of Estimate
Depot		
Engine - Overhaul and Repair	$200/FH	"B" Report plus Burdens
Component Repair (F/E)	$150/FH	From Equivalent Air Force Data (MISTR account)
Modifications	$ 30/FH	From equivalent Air Force data
Subtotal	$380/FH	
Base		
Test Fuel	$ 20/FH	From equivalent Air Force data
Base Labor	250/FH	manpower loading
Base Material	25/FH	
Total Cost	$675/FH	

Repair of components removed from engines (F/E account), at $150/FH in this estimate, cost almost as much as engine repair. Engine modifications had been overlooked, also. Material and test fuel have been added and manpower loading was used to derive labor cost. This is still not a precise calculation but is much closer to the truth.

Recent Air Force studies have also provided new insight into engine support cost. (See figure 5.) Organizational and Intermediate level costs can be obtained from the Maintenance Cost System (MCS) which is fed by the Maintenance Data Collection System (MDCS) plus a parts usage record system usually referred to as U 1050 — II. This data is useful after carefully excluding exchangeables and initial provisioning. These exchangeables later show up in depot costs as MISTR (Management Items Subject to Repair) items. Initial provisioning, of course, has no place in a consumption-oriented calculation.

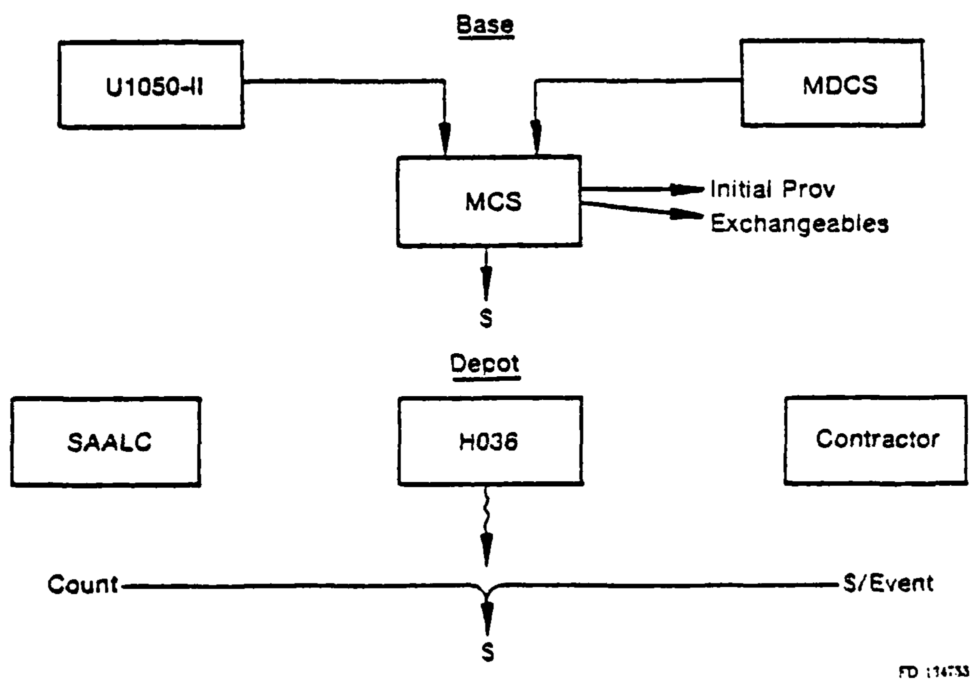

Figure 5. Support Cost Derivation

Depot costs can be obtained in a usable form by tapping various systems which input to the HO 36 system, although not directly from HO 36. These costs can be checked by using Air Force depot "counts" of repairs by type of repair performed multiplied by costs per event for similar work performed at contractor facilities.

This Air Force study, plus three earlier small studies of support data at Navy facilities, plus continuous efforts connected with current engine programs have shown a pattern of problems which are now being dealt with. Problems generally relate to inaccuracy, inconsistency, omissions and overlap. Below are examples:

- Count of items not repairable this station (NRTS) or beyond capability of maintenance (BCM) from the base to the depot are often not in agreement with count of items received at depot.
- Air Force 66-1 and Navy 3M systems omit up to 40% of maintenance actions.
- Air Force has directed maintenance bases to cease collecting data on "shop work" i.e. labor expended on engine build-up and tear-down not charged to 23000 series work unit codes. There is even a possibility that even more of the 66-1 data may be eliminated.
- Maintenance records are not related to cause (How Mal Codes) in depot data although internal engine failures are discovered only at depot.
- Reluctance to release data at some locations.
- Cost data is often not relatable to quantities of engine or items repaired.
- Translation among Item Ident. Codes, National Stock Number, Part Number and Job Number is often difficult.
- Many records do not distinguish between engine models — list aircraft only.

As discussed earlier the necessity of distinguishing provisioning data from consumption data. This is because engine support cost assessments, and subsequently engine support cost predictions, must be based on engine faults or consumption of parts and labor. Data based on allocation or provisioning, although more readily available, is a function of management philosophy as well as of engine characteristics. Such allocation costs are often reported, and have even been divided by engine flight hours and reported as a rate. The resulting curve looks like that in figure 6. Note that early in a program when provisioning is heavy and FH are few, the cost per flight hour is quite high as contrasted with the consumption curve for the same time period based on consumption. These curves should, in theory, cross over as early provisioned parts are consumed. The slope of the consumption curve in early years is not obvious to this observer. The compensating effects of maturing the engine by solving early problems (downward slope) and the aging of the engine population with more modules reaching durability limits (upward slope) could slope the cost per FH curve either way.

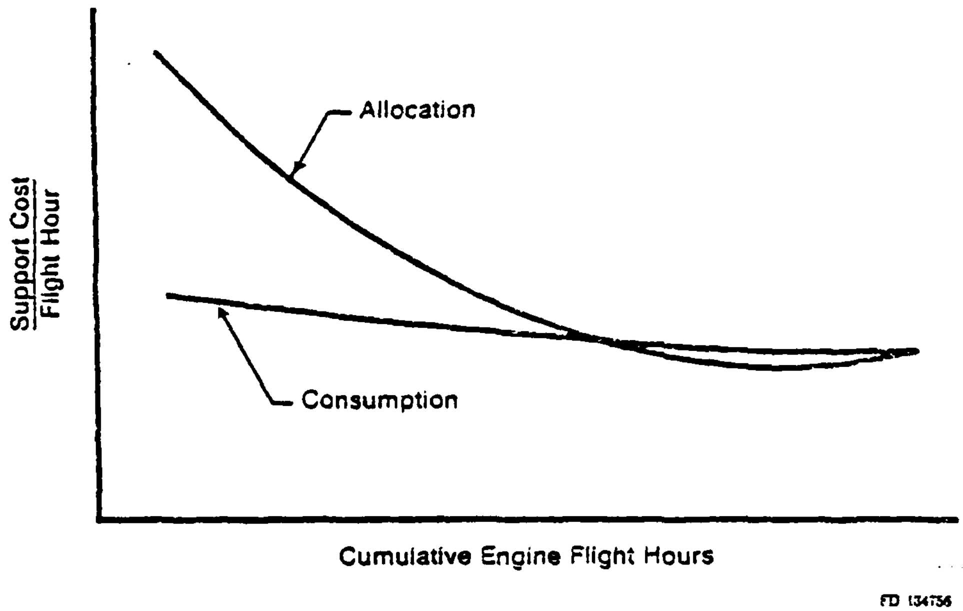

Figure 6. Support Cost Per Flight Hour Should Be Based on Consumption

Solutions

An increasing awareness of support cost as a major portion of the defense budget is now prompting a more effective use of current operating experience. For example, Navair/NADC have now launched a program that will retrieve and analyze fighter engine support cost data, then derive a support cost prediction model as a function of engine Design characteristics. Data is being gathered at seven different maintenance facilities plus two records centers and from all maintenance levels. Data will be compiled at the most detailed level, opening the way for accurate treatment of that most important and most difficult element of any LCC model, engine support cost. The study tasks can then be summarized as:

- Determine actual engine maintenance costs and relate to engine faults using TF30 and J52 as a study base
- Relate these costs to engine design and duty cycle — thus deriving a maintenance cost prediction system
- Recommend improvements in existing cost data systems and maintenance practices.

This model will be of the CER type mentioned above and provide an assessment tool to be used with engine data which would be available prior to and during source selection.

This and similar studies by other agencies will allow accurate LCC analysis by the military of alternative engine offerings. Contractors will be better able to set cost-oriented goals and address the feasibility of Reliability Incentive Warranties. As engines enter service, provisioning can be accomplished with a more thorough knowledge of quantities required. And perhaps most significant of all, engine designs can be better optimized to produce more cost effective aircraft systems.

THE ROLE OF TURBINE ENGINE

TECHNOLOGY ON LCC

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ABSTRACT

The turbine engine is a major contributing subsystem in the life cycle cost (LCC) of an aircraft weapon system. The impact of turbine engine technology on LCC is addressed in this paper. To adequately assess this technology, LCC techniques are being developed which are sensitive to performance, structural design, manufacturing processes, reliability and maintainability. These techniques will then be used to determine the performance/life/cost trade-offs of advanced technology. An overview of current efforts in this area is given.

INTRODUCTION

The overall objectives of our efforts in the area of life cycle cost (LCC) are two: first, to determine the cost impact of our advanced technology, and second, to identify and pursue those technologies which offer the greatest potential in cost reduction. This briefing will include a perspective of turbine engine LCC, and then an overview of current efforts on the methodology and application of design-to-life-cycle-cost.

Chart 1 shows the life cycle cost of the top five subsystems of an advanced fighter weapon system. The cost of each subsystem is shown as a percentage of total system production cost and logistics support cost. As can be seen from this chart, the engine subsystem is a major component of weapon system cost.

LIFE CYCLE PHASES

In the development phase, the major cost drivers are hardware and test. A study of previous engine development programs suggests that a relationship exists between these two parameters. Current efforts are being conducted, using these parameters, to develop estimating relationships for the development phase.

In the acquisition phase, previous cost estimating efforts for this phase determined that the single most significant parameter in estimating the acquisition (or production) cost of an engine is its thrust. It follows then that the cost per pound of thrust is a relative measure of the acquisition cost of an engine. Chart 2 is a graph of cost per pound of thrust, for engines in the inventory, plotted against their Military Qualification Test (MQT) date. The cost of engines was normalized to constant year dollars and equivalent production rate and production quantity. The slope of the curve shown is a measure of the increase in cost of engines over the last 30 years. This increase is a moderate one.

ADV. FIGHTER SUBSYSTEM LCC
(TOP FIVE SUBSYSTEMS)

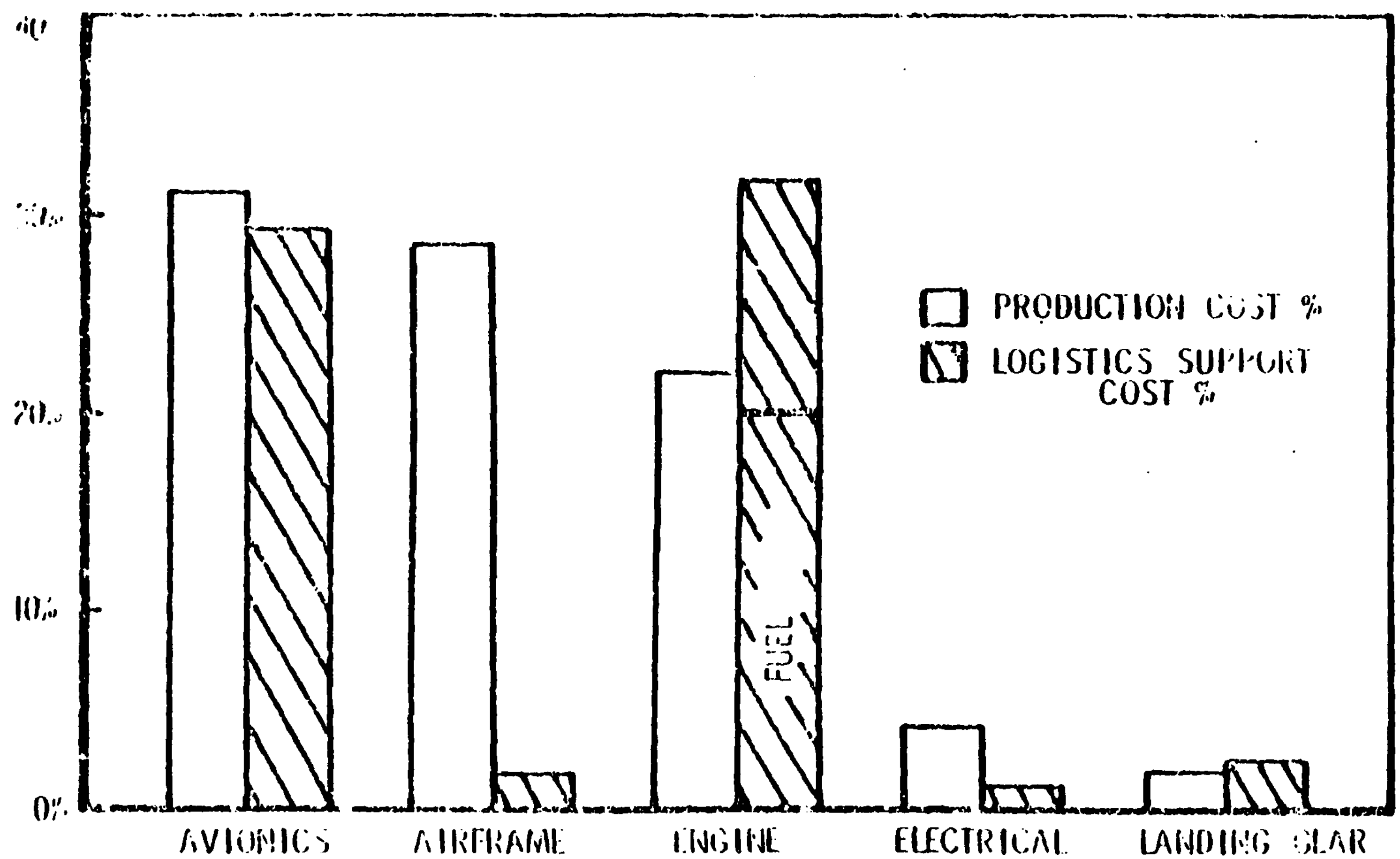


Chart 1

ENGINE COST TREND

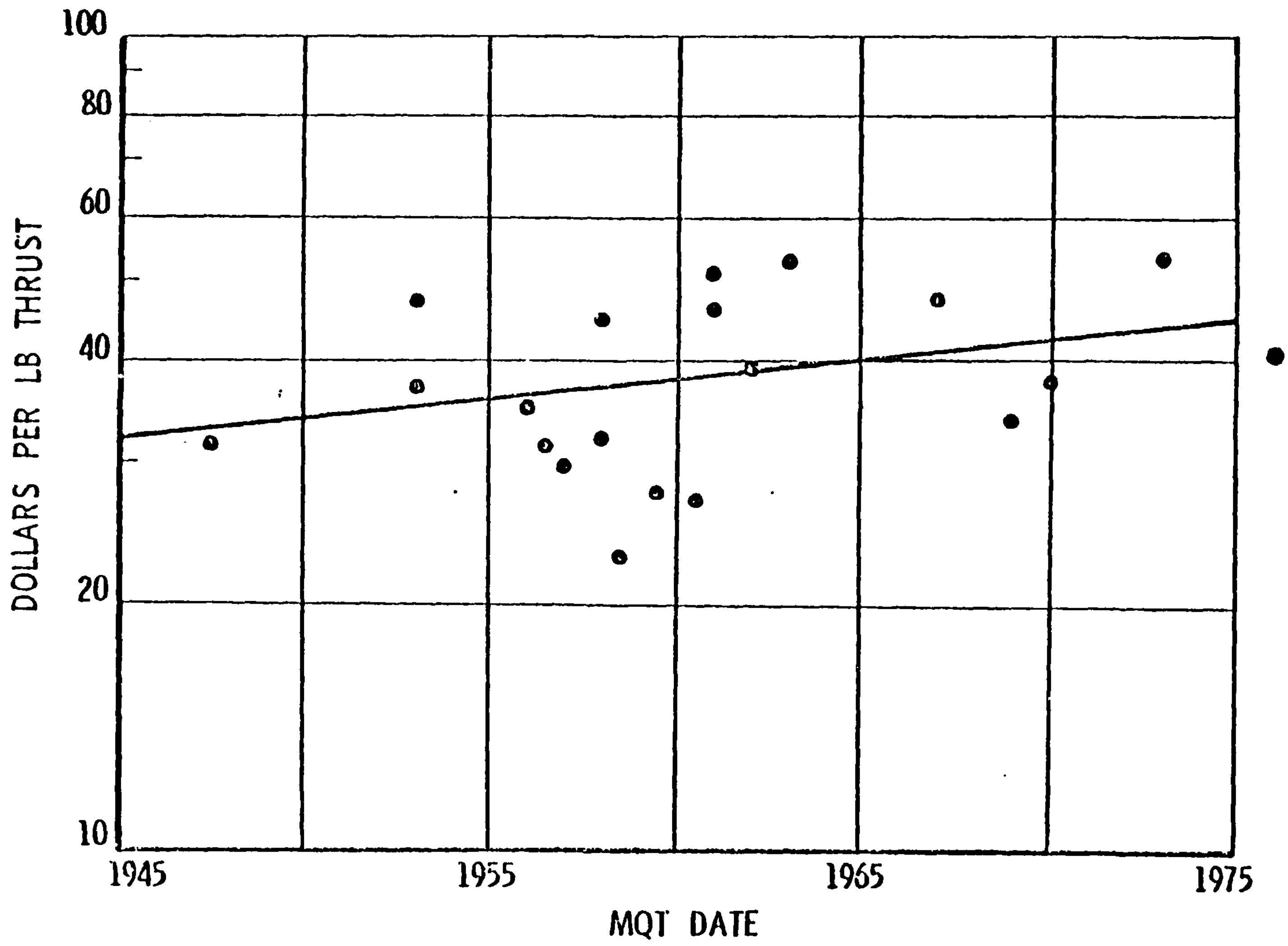


Chart 2

In estimating the cost impact of advanced technology, it is possible to be too narrow in scope, and therefore the analysis can lead to erroneous conclusions. For example, consider the bore entry design of a turbine disk compared to the more conventional rim entry design. Chart 3 is a cross-section schematic of the rotating assembly of the gas generator. Shown are the compressor assembly (minus blades), shaft, and turbine wheel. The primary difference between the design in the upper half of the schematic, and the design in the lower half is in the turbine area. The upper half shows bore entry turbine cooling, the lower half shows rim entry turbine cooling. The relative production cost of the two-disk designs is shown on the chart. The relative cost of the bore entry disk is more than two times that of the rim entry disk. However, if the rotor cost is estimated for those parts shown on the chart, the relative cost of the two rotors are approximately equal, as shown on the right of the chart. This is so because the secondary flow system, in the case of the bore entry design, is simpler. It is important that the scope of the analysis be broad enough to identify the impact of the advanced technology.

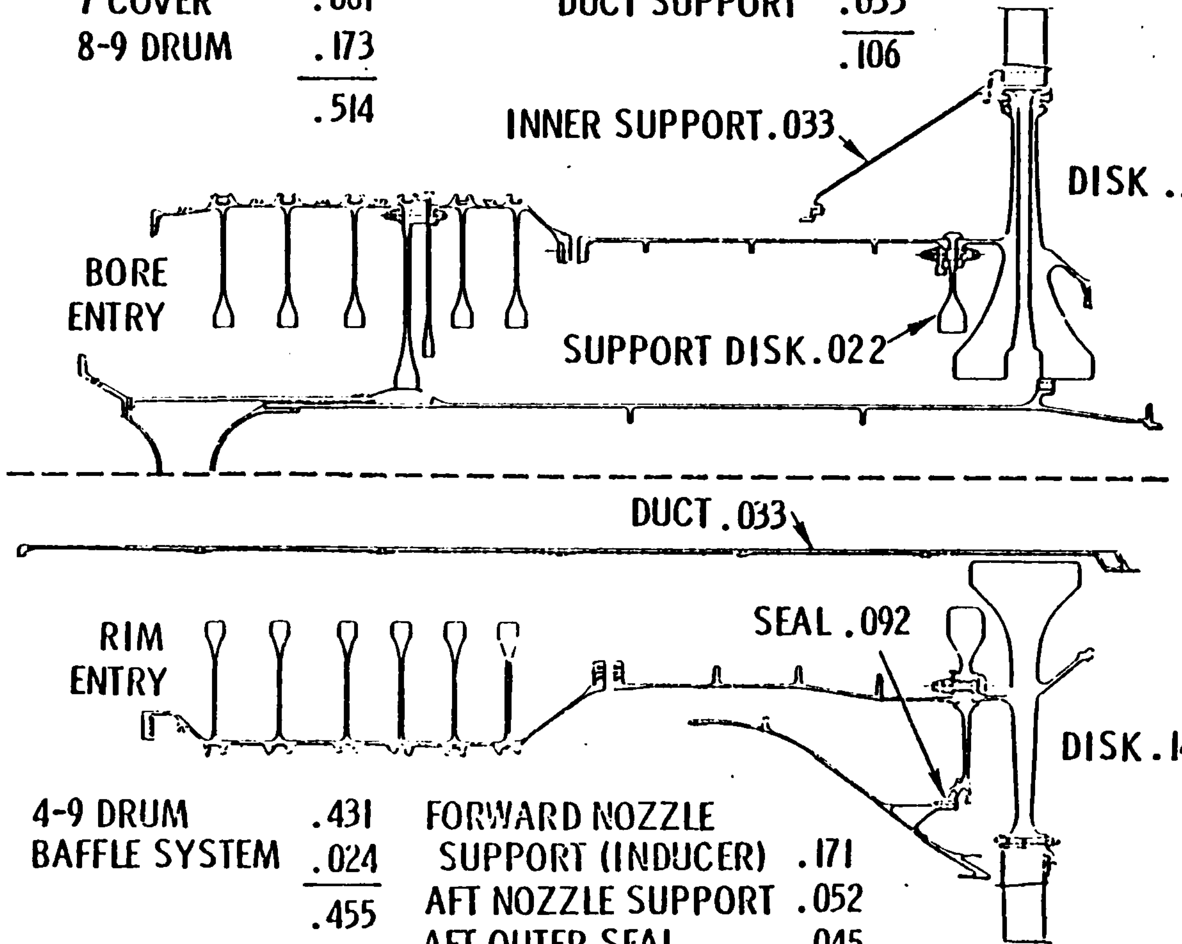
Let us now consider the operations phase. One of the difficulties in this phase is summarized in a Government Accounting Office (GAO) report, dated Dec 74, which states, "It is almost universally held that the greatest obstacle to preparing reliable life cycle cost estimates is the absence of a data base segregating total ownership cost by weapon." However, we are making gains in this area. Hardware failures in the operational phase are a cost driver. Chart 4 shows the basic causes of engine failure, and the approximate percentage of failures attributed to each cause. Some of the causes are well understood, others are not. A difficulty encountered in understanding failures, is the combination of two or more basic causes contributing to a failure. The mechanism of failure of these combined causes is difficult to analyze, and the failure difficult to predict.

The operational use of the engine is a major factor in determining its operational and support (O&S) cost. Efforts are going on to understand and quantify this usage effect. Chart 5 is a set of graphs comparing the engine related operational characteristics of two airplanes flying formation. As can be seen from the graphs in Chart 5, the power setting, engine speed, and tailpipe temperature for the wingman are considerably different than that of the flight leader, even though both airplanes are flying at the same speed and altitude. The resultant temperatures, pressures, and stresses throughout the engines are quite different, and, hence, the useful life of the engines can be significantly different. Chart 6 is a pictorial summary of major efforts to predict life of engine components. The tasks to be accomplished to make these predictions and validate them, are shown on the chart.

Fuel is becoming a very important factor in the O&S phase. Chart 7 shows the Air Force cost and consumption of fuel for the last five years. The vertical bars represent the amount of fuel used, and the curve represents the cost of fuel, in cents per gallon, over the time period shown. Both cost and availability of fuel will continue to be an important factor.

Cost Estimates for Bore Vs. Rim Entry Study Engines

4-6 DRUM	.204	DUCT	.020
7 DISK	.076	AFT TUBE	.051
7 COVER	.061	DUCT SUPPORT	.035
8-9 DRUM	.173		.106
	.514		



4-9 DRUM	.431	FORWARD NOZZLE SUPPORT (INDUCER)	.171
BAFFLE SYSTEM	.024	AFT NOZZLE SUPPORT	.052
	.455	AFT OUTER SEAL	.045
			.273

Bore entry	Rim entry
.514	.455
.106	.092
.033	.147
.022	.033
.341	.273
1.016	1.000

$$\boxed{\begin{array}{r} 1.016 \\ 1.000 \\ \hline .016 \end{array}}$$

Chart 3

CAUSES OF ENGINE FAILURES

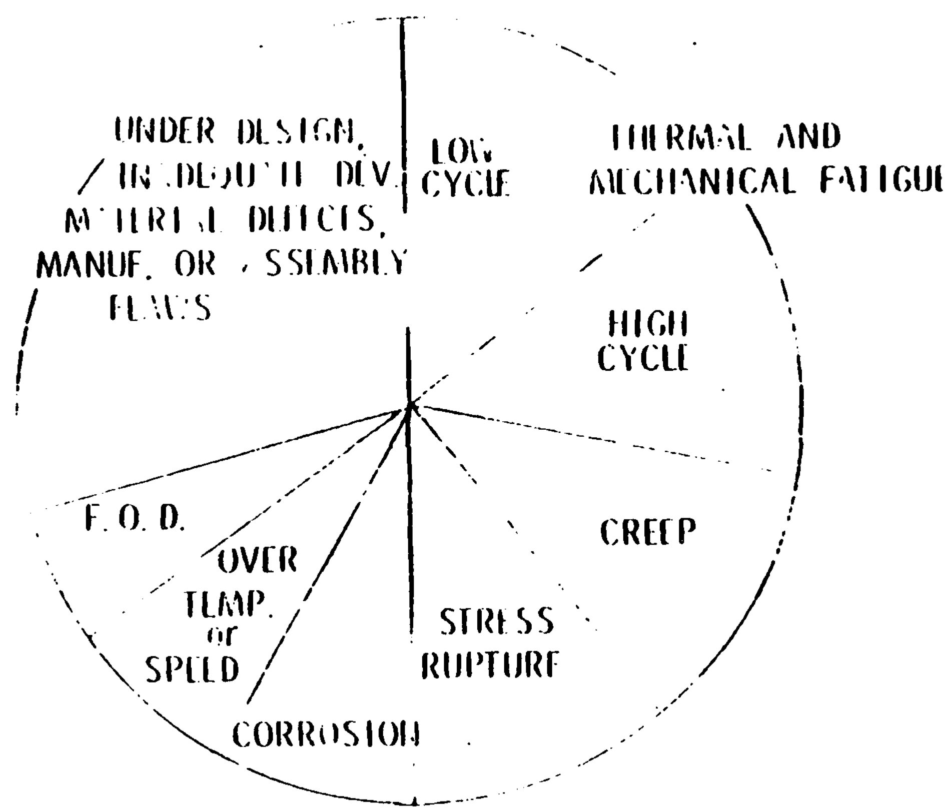


Chart 4

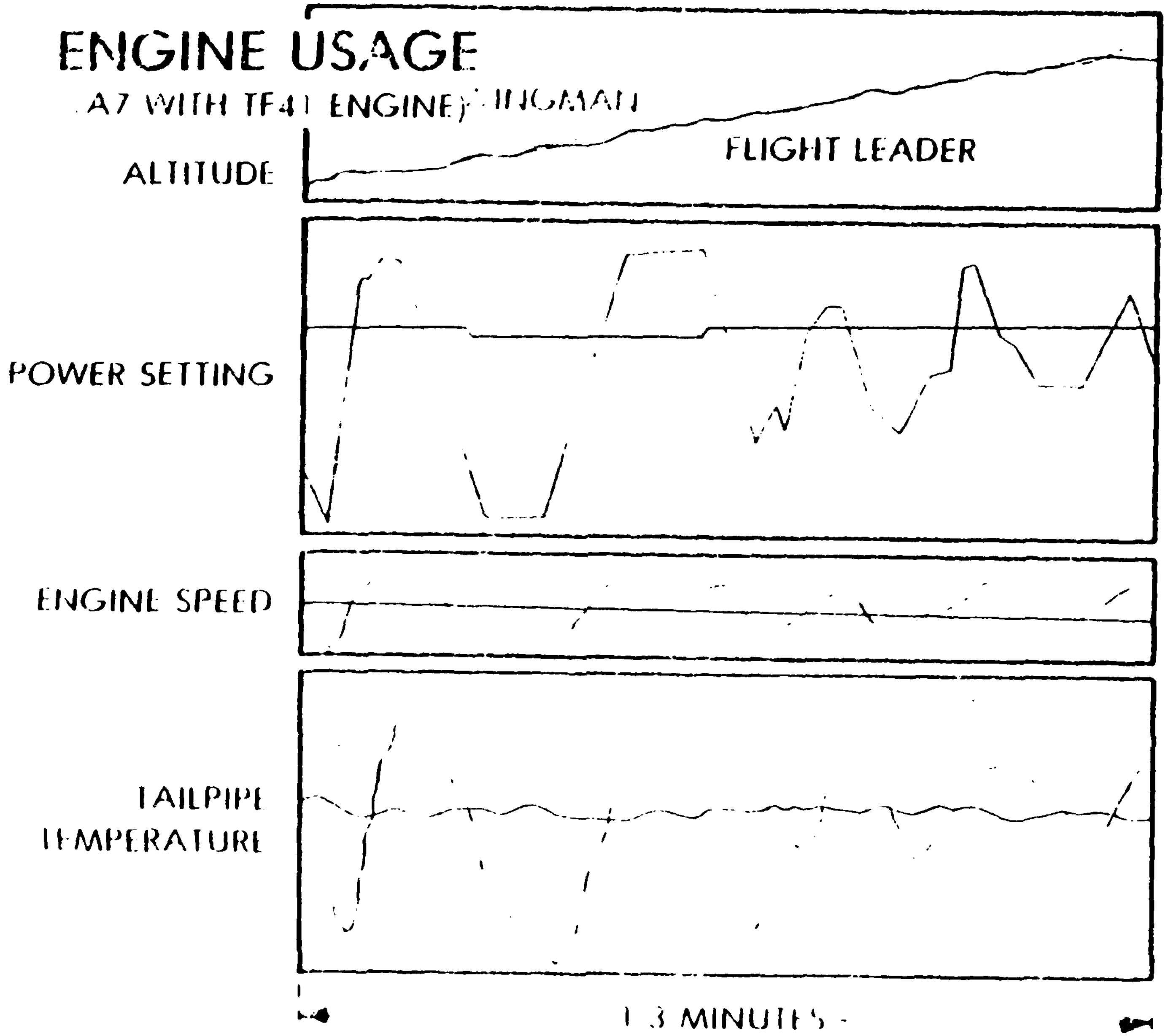
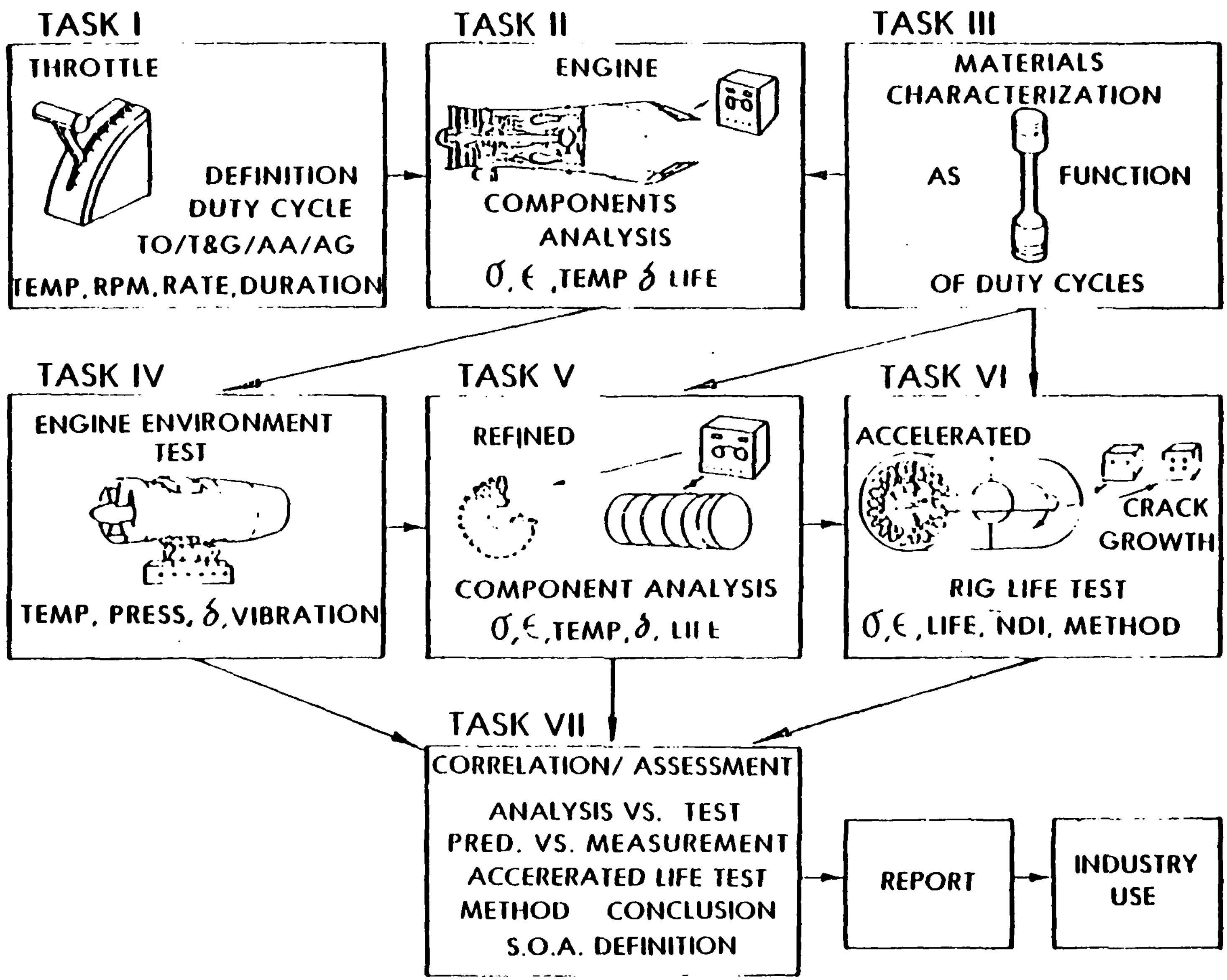
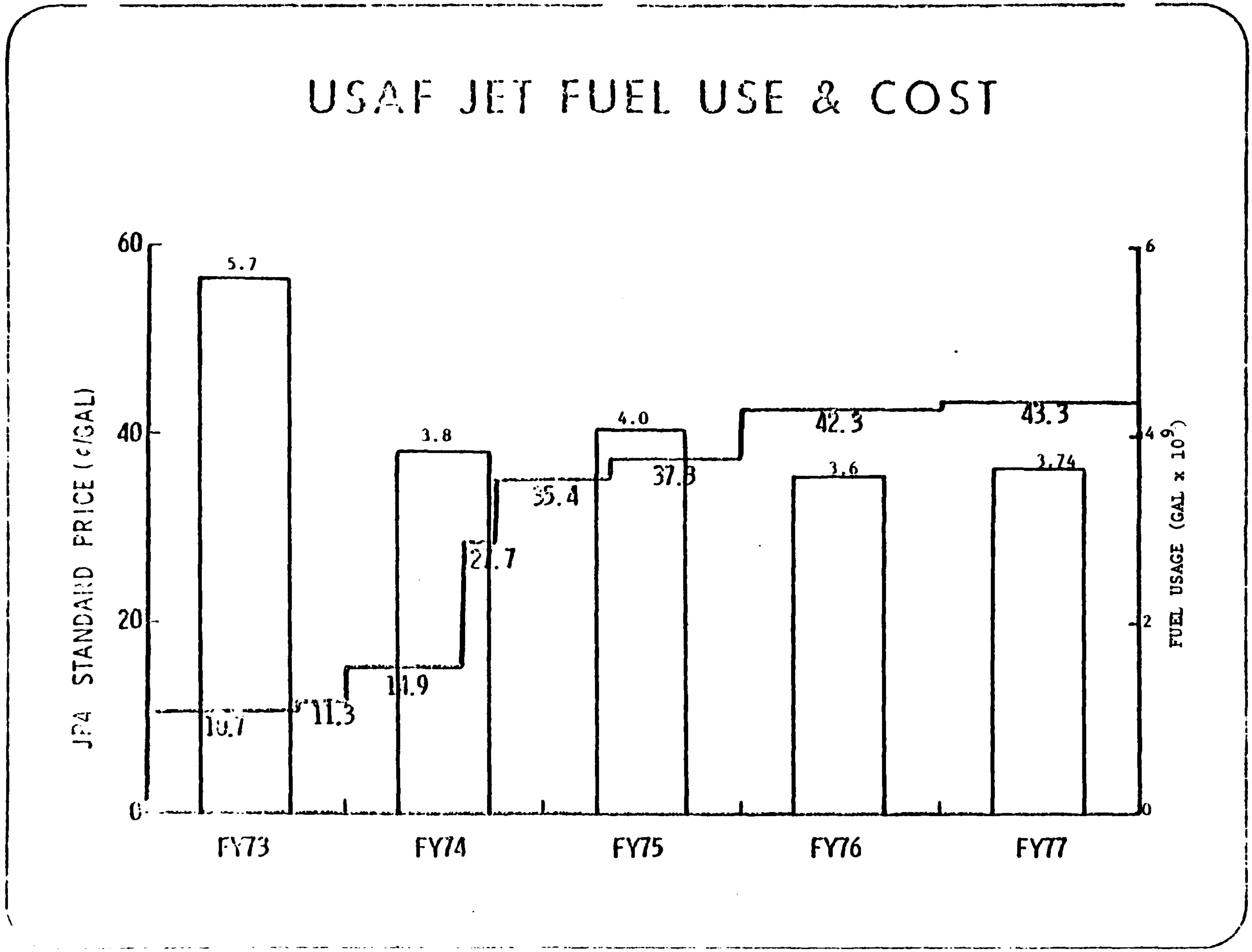

ENGINE USAGE
A7 WITH TF41 ENGINE
WINGMAN
FLIGHT LEADER
ALTITUDE
POWER SETTING
ENGINE SPEED
TAILPIPE TEMPERATURE
3 MINUTES

Chart 5

STRUCTURAL LIFE PREDICTION/CORRELATION



Chart



USAF JET FUEL USE & COST
JP4 STANDARD PRICE (¢/GAL)
FUEL USAGE (GAL x 10^9)
60
40
20
0
6
4
2
0
5.7
3.8
4.0
3.6
3.74
10.7
11.3
11.9
21.7
35.4
37.8
42.3
43.3
FY73
FY74
FY75
FY76
FY77

Chart 7

DESIGN TO LIFE CYCLE COST

There are major efforts underway to define a methodology for life cycle cost analysis, and to apply that methodology to advanced technology programs. In June 1977, the Reduced Cost Turbine Engine Concepts program was initiated. The objectives of this effort are to: (1) assess reduced cost turbine engine concepts prior to engineering development in terms of their impact on engine research, development, test and evaluation (RDT&E) cost, engine acquisition cost, engine O&S cost, and system LCC; (2) select an engine component concept which offers significant cost reduction based on this assessment; (3) design, fabricate, and test the selected component concept; and (4) reassess the component concept LCC impact based upon the design, fabrication and test results. This effort will demonstrate the use of LCC as a major design parameter.

Reduced Cost Turbine Engine Concepts Approach

The Reduced Cost Turbine Engine Concepts Program will first develop an LCC model to determine engine RDT&E cost, engine acquisition cost, engine O&S cost and system LCC as a function of turbine engine component design parameters. These component design parameters will include performance, weight, life, maintainability and acquisition cost. The LCC model will then be used to determine the LCC of some advanced technology aircraft system for use as a baseline. Trade studies will then be conducted relative to this baseline. The results of the trade studies will be used to select a component concept for design, fabrication and test. As data is obtained during the design, fabrication, and test phases, the LCC model will be updated and the impact on LCC determined.

Reduced Cost Turbine Engine Concepts LCC Model

The cost elements used in the LCC model to define turbine engine LCC were obtained from the Air Force Industry Turbine Engine Life Cycle Cost model dated Feb 1977. This model is the result of work conducted in the 1975 to 1976 time period by a group composed of Air Force and Industry personnel. A paper entitled, "Calculating Turbine Engine LCC", by Mr. Michael A. Barga, to be given in this seminar, describes the work done by this group. Chart 8 lists the cost elements defined by this model. Not all cost elements given on Chart 8 will be used in the developed model. The equations marked with an "X" will be used in the appropriate LCC phase. For example, cost element 3 will be used during RDT&E and O&S. Equations were selected for use on the basis of their percent contribution to engine LCC. For example, results to date indicate that Scheduled Maintenance accounts for 35% of engine LCC, Petroleum, Oil, and Lubrication accounts for 28% of engine LCC, and Engine Manufacturing accounts for 23% of engine LCC. The other cost elements given on Chart 8 account for the remaining 14% of engine LCC.

The LCC model to be developed by this effort uses both accounting and parametric cost estimating relationships. Chart 9 gives examples of parametric cost estimating relationships and accounting cost estimating relationships. A parametric cost estimating relationship is an empirical

REDUCED COST TURBINE ENGINE CONCEPTS

LIFE CYCLE COST MODEL

COST ELEMENT	R	A	S	COST ELEMENT	R	A	S
1. Conceptual Study, Cycle and Configuration				15. Contractor Field Support			X
				16. Data			
2. Mock-up				17 Initial Inventory Management			
3. Detail Design	X		X				
4. Tooling	X	X		18. Recurring Inventory Management			
5. Engine Manufacturing	X	X	X				
6. Spare Sections Assemblies and Parts	X	X		19. Scheduled Maintenance	X		X
				20. Unscheduled Maintenance			X
7. Peculiar Support Equipment				21. Recurring Maintenance Management			
8. Common Support Equipment							
9. Special Test Equipment	X			22. System Engineering/ Project Management	X		
10. Packaging and Shipping			X				
11. Facilities				23. Petroleum, Oil and Lubrication	X		X
12. Contractor Test	X						
13. Government Testing				24. Production Program Start-up			
14. Training							

R - Research Development Test and Evaluation

A - Acquisition

S - Operation and Support

Chart 8

REDUCED COST TURBINE ENGINE CONCEPTS

LIFE CYCLE COST MODEL

PARAMETRIC (COST ESTIMATING RELATIONSHIPS)

COST = f (THRUST, WEIGHT, ETC.)

ACCOUNTING

$$\text{COST} = \sum_{i=1}^{n} \left[(\text{LABOR RATE}_i)(\text{MAN-HOURS}_i) + (\text{MATERIAL WEIGHT}_i)(\text{MATERIAL PRICE PER POUND}_i) \right]$$

n = TOTAL NUMBER OF PARTS

Chart

equation for some element of cost in terms of design parameters. An accounting cost estimating relationship is a summation of labor costs, material costs and overhead costs.

Chart 10 is a simplified schematic of the LCC model to be developed by this program. The model will calculate engine RDT&E cost, engine acquisition cost, engine O&S cost and system LCC as a function of engine component life, weight, performance, maintainability and acquisition cost. Engine RDT&E costs will be calculated using parametric cost estimating relationships. Engine acquisition costs will be calculated using accounting cost estimating relationships. Costs will be accumulated at the component level. Learning curves will be used to account for changes in cost with production quantity. Scaling laws will be provided to account for changes in baseline engine size. Engine O&S costs will be calculated using either a simulation or a discrete model. A complete explanation of a simulation versus a discrete model is beyond the scope of this paper. It will simply be stated that the simulation model provides a more realistic representation of the O&S phase of the engine life cycle. The discrete model has the advantage of using less computer time and storage. Both models account for scheduled maintenance as a function of engine operating hours, flights or periods and employ learning curves for required maintenance actions. Both models account for unscheduled maintenance by employing failure distributions for individual engine components and learning curves for resultant maintenance actions. Fuel is determined as a function of usage and engine fuel flow. All phases of airframe LCC will be determined using parametric cost estimating relationships. These cost estimating relationships will define airframe RDT&E, Acquisition, and O&S costs in terms of engine and airframe interface parameters. These cost estimating relationships will be developed for the baseline aircraft by an airframe subcontractor. In the future, it is planned to use the system life cycle cost model currently being developed by the Air Force Flight Dynamics Laboratory, Chart 11. The developed model will use inflation, discounting or constant year dollars.

Reduced Cost Turbine Engine Concepts Methodology

All LCC trade studies will be conducted relative to the baseline system LCC. During these studies, the following parameters will be constant: mission, lifetime, fleet buildup and peacetime usage rates. The baseline engine and airframe will be scaled in size to meet fixed mission requirements, and the cost impact then determined. The trade studies will be conducted applying inflation and discounting, and constant year dollars.

Chart 12 shows that a change in baseline engine component performance will require the use of an engine performance model, an aircraft sizing/mission analysis model and the LCC cost model. A change in baseline engine component weight will require a reassessment of baseline engine weight, resizing of the baseline aircraft, and the use of the cost model to determine the cost impact. Changes in baseline engine component life, maintainability, and acquisition cost require only the use of the LCC model.

REDUCED COST TURBINE ENGINE CONCEPTS

LIFE CYCLE COST MODEL

ENGINE

RDT&E

- Cost Estimating Relationships (CER)

ACQUISITION

- Part Level
- Learning Curves
- Scaling

O&S

- Fuel
- Scheduled Maintenance
  - Operating Hours
  - Flight
  - Period
  - Learning Curves
- Unscheduled Maintenance
  - Failure Distributions
  - Learning Curves

AIRFRAME

RDT&E

- CER

ACQUISITION

- CER

O&S

- CER

ECONOMICS

- Inflation
- Discounting
- Constant Year Dollars

Chart 10

FLIGHT DYNAMICS LABORATORY SYSTEM LIFE CYCLE COST MODEL

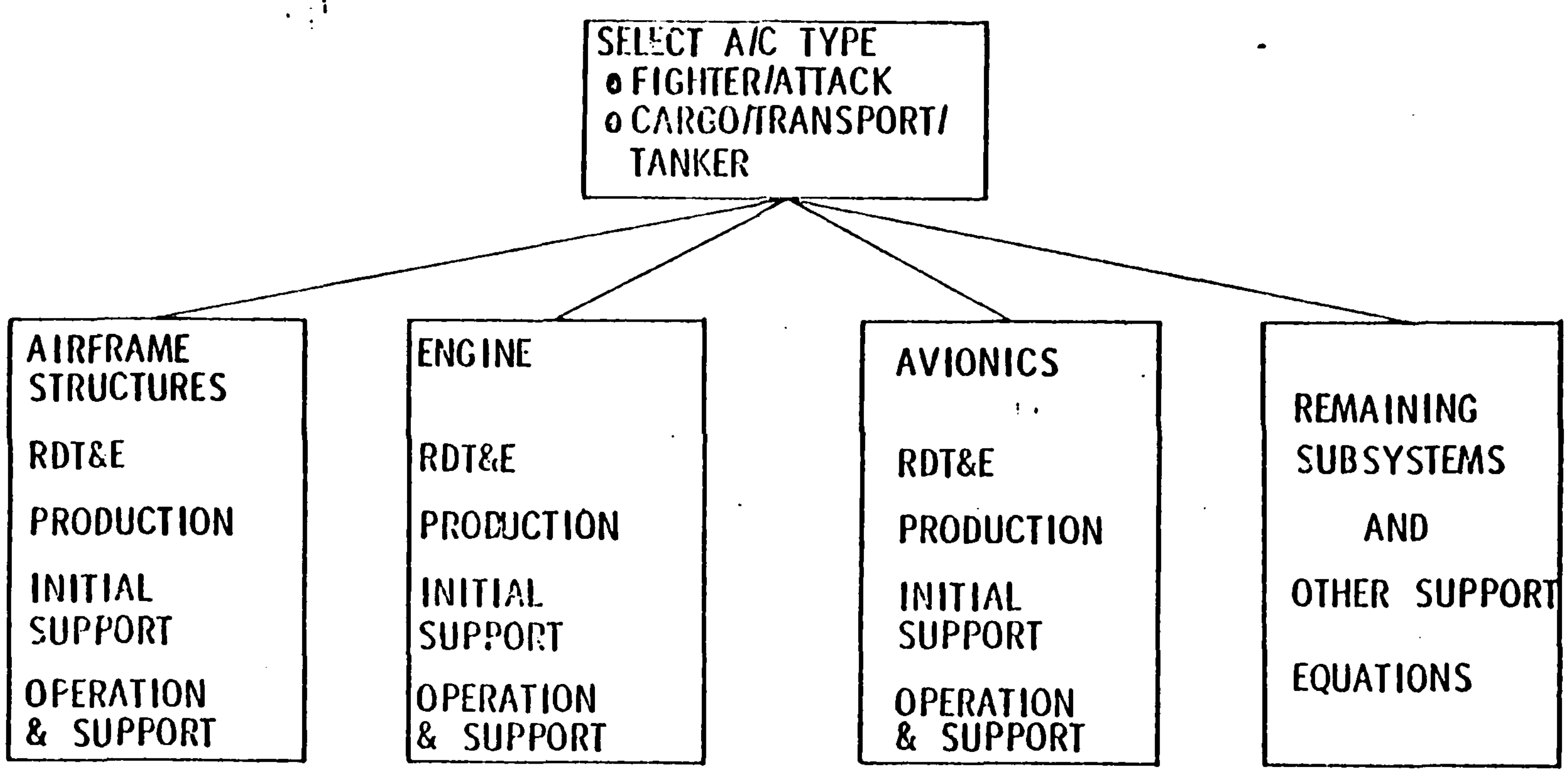
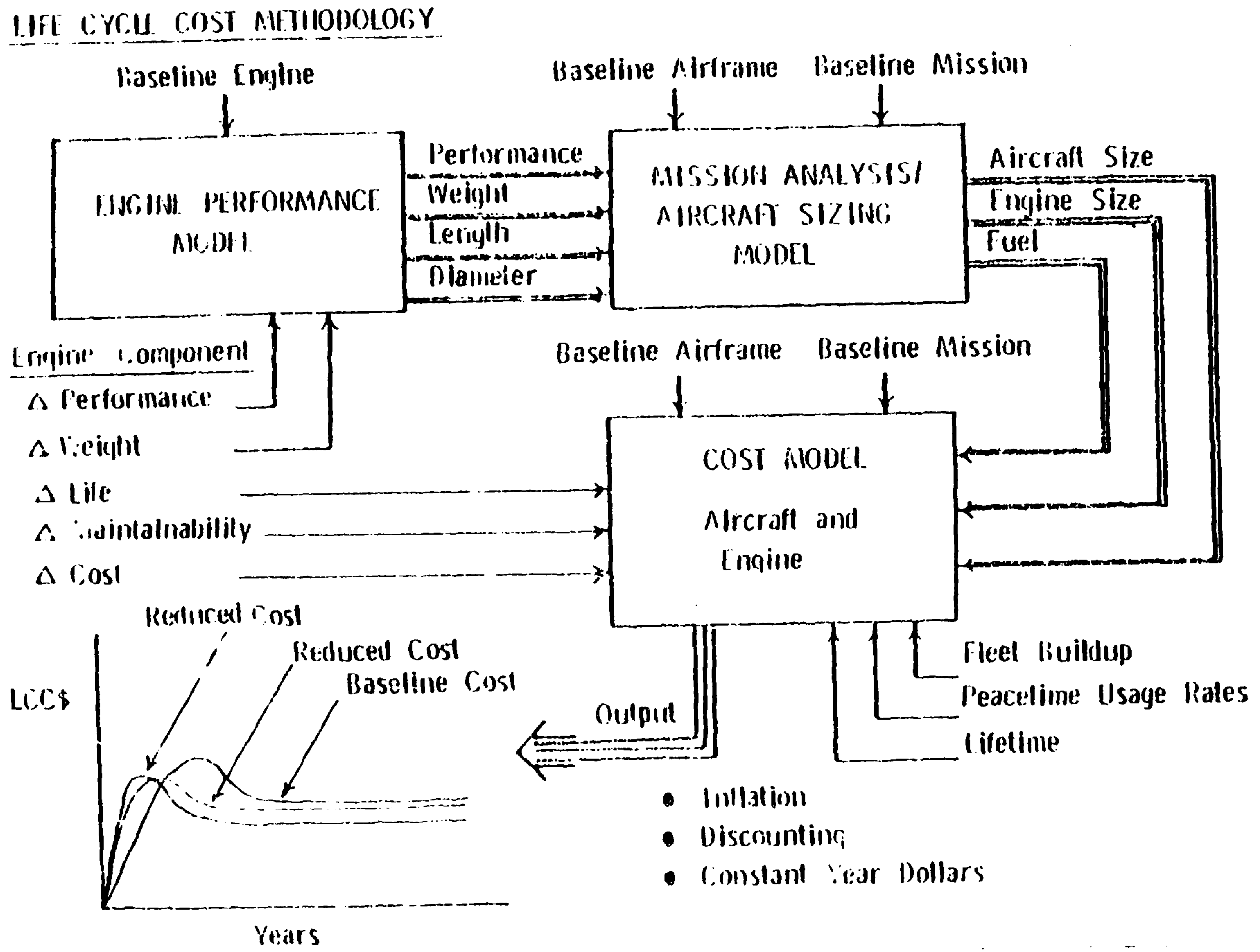


Chart 11

REDUCED COST TURBINE ENGINE CONCEPTS



CONCLUSIONS

An assessment of the payoff of advanced technology must include the effect of three fundamental characteristics of that technology. These characteristics are performance, structural life, and cost. Chart 13 shows what this assessment process involves when applied to turbine engine technology. As the chart shows the assessment is involved, and the performance, structural life, cost characteristics are very much interactive.

PROPULSION SYSTEM

INSTALLED PERF • STRUCTURAL/LIFE • LCC/DTC

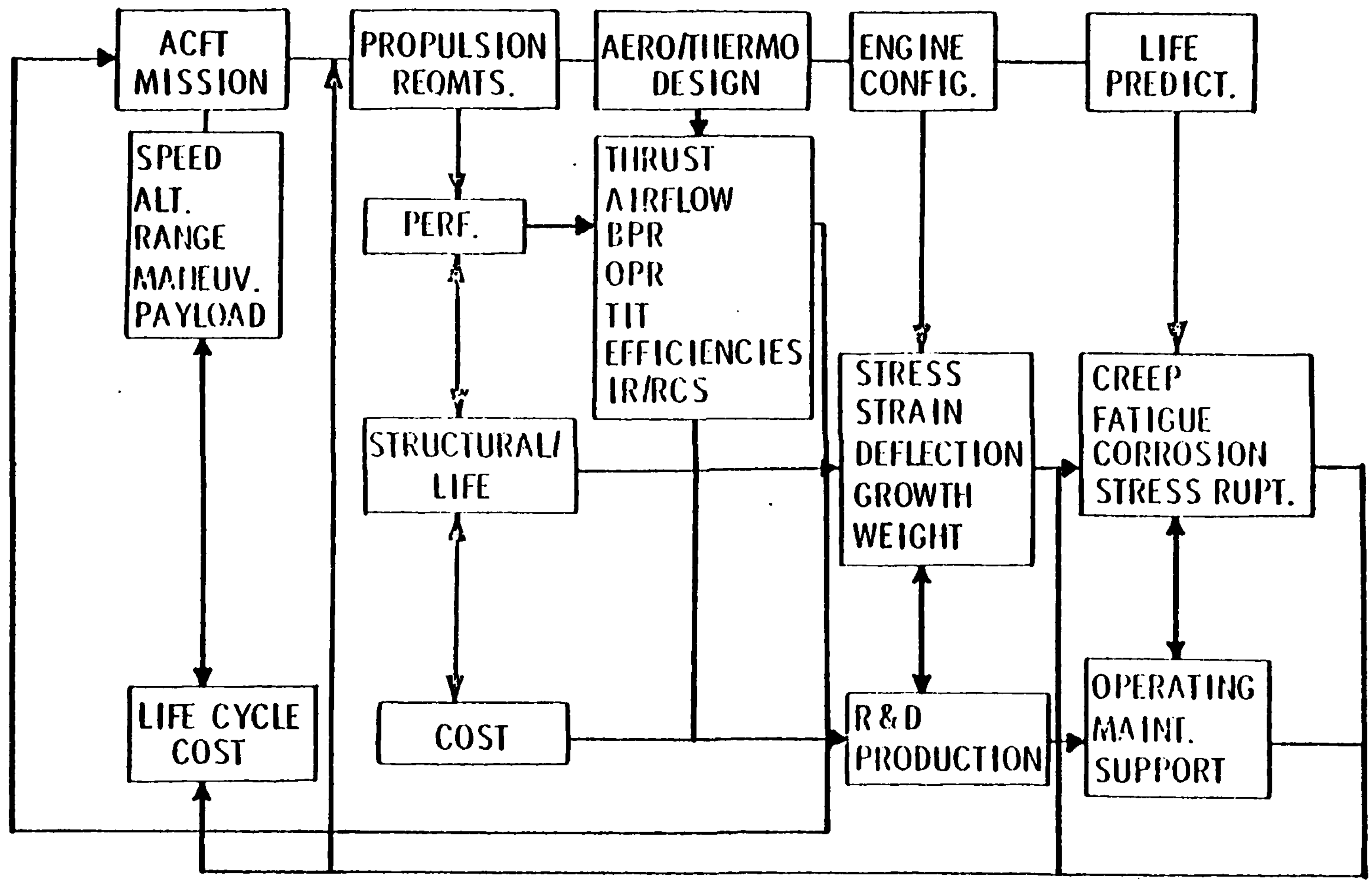


Chart 13

F404

DESIGNED FOR LOW LIFE CYCLE COSTS

By
J. Stephen Bradley
Aircraft Engine Group
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Lynn, Massachusetts

ABSTRACT

Carlton E. Curry

Staff Systems Analyst

Detroit Diesel Allison

Indianapolis, Indiana

Military Aircraft Engine Life Cycle Cost From
A Commercial View

A review of commercial maintenance practices used to minimize the operation cost of helicopter turbine engines is compared with current military practices. The impact on Life Cycle Costs are discussed for each maintenance philosophy. Suggestions for reducing military aircraft engine cost of ownership are made together with a brief summary of concerns associated with the suggestions.

C. E. Curry
30 January 1978

INTRODUCTION

Back in 1975, those of you who attended the OSD, LCC Seminar were given an introduction to the General Electric F404 Engine. Much of that information was qualitative, or based on early calculated numbers, because after all, there was no F404 engine in existence at that time.

Since then we have come a long way. In late 1975, General Electric and the U.S. Navy inked the contract to begin Full Scale Development of the F404 for the F-18 Naval Strike Fighter, now known as the "Hornet". In January 1977, the first F404 engine went to test, and today we are nearing completion of the PFRT with initial flight testing starting later this year.

This, then, is a good point to review the F404 LCC requirements, their implementations during design and development, the results to date, and some lessons learned for the future.

BACKGROUND

To start, I would like to review the history behind the F404 engine, as its background forms an important base upon which the current engine has been built.

In the early seventies it became apparent to General Electric that a new engine stressing simplicity through technology would be needed to fill the requirements of a low cost fighter design. This fighter would eventually replace aircraft such as the F4's and F104's, and compliment the higher cost F-14's and F-15's. Working with Northrop's concept for light-weight advanced fighters, General Electric began to define, design and build components for such an engine. In 1972 a contract was signed with the Air Force to continue the development program through a "prototype PFRT" and to supply engines for the YF-17 light-weight fighter program. The engine was then designated the YJ101 and it is from this engine that the F404 is derived (Fig. 1). Therefore, the F404 that is under development today is not a brand new engine concept, but it is derived from the very successful YJ101 whose design was driven by a major emphasis on design simplicity and low cost.

F404 DEVELOPMENT - CONTRACTUAL LCC REQUIREMENTS

In the 1975 time period when the F404 development contract was being prepared, the state of the art was not sufficiently advanced to specify, measure, incentivise, etc., Life Cycle Cost. What was done instead, was to devise a

program with major emphasis on those factors which were known to be the most significant contributors to Life Cycle Cost. In particular:

1. Reliability
2. Maintainability
3. Unit Acquisition Cost (which directly effects spare parts costs)

The Contract also requires use of LCC analysis as a reporting requirement and a decision making tool.

RELIABILITY

Reliability is obtained during the development phase as a result of an extension of the program in duration, engine hour accumulation, and use of representative test cycles. The development program (Fig. 2) is long enough to allow sufficient time for TAAF (Test, Analyze and Fix) programs. This assures that possible problems are evaluated and fixed before the engine goes into production. Development testing cycles are also designed to match expected operational environments. In particular, extensive Simulated Mission Endurance Testing (SMET) and Accelerated Service Testing (AST) are included in the development program to increase the maturity of the engine as it goes into Production. Figure 2 is a comparison of some of the F404 development testing requirements versus typical earlier programs.

Specific reliability requirements exist at several points in the development program. Reliability tracking occurs continuously, and the first key requirement occurs during the 750 hour SMET test. Substantial incentives exist in varying amounts, depending upon the degree to which Reliability is achieved during SMET.

Subsequently, the impact of Reliability is included in the maintenance measurements during the AST portion of the test program (see below). Lastly, Reliability is measured at the 5000 aircraft flight hour point.

MAINTAINABILITY

Maintainability requirements are included in the contract via maintenance demonstration requirements during development, as well as measurements made during AST. These measurements are not a factory demonstration; but are the result of experience during the Navy portion of the 1000 hour AST, using Navy personnel. The requirements include maintainability specifically, (mean time to Repair, maintenance man hours per engine operating hour, maximum repair time), and cost (spare parts cost per engine flight hour, total support cost per engine flight hour). All of these requirements are incentivised also.

ACQUISITION COST

Reliability and Maintainability can be measured during the Development phase, particularly during extended testing such as SMET and AST. Cost, however, cannot be accurately proven until the production engines are built and delivered.

Accordingly, the Cost requirements on the F404 extend well beyond the Development phase. In fact, the sell prices to the Navy for the first 520 Design-to-Cost (DTC) production engines to be delivered in the 1980 to 1984 time period, are specified in the Full Scale Development contract. Cost underruns (or overruns) as determined by comparing the out year prices with those specified in the contract, are subject to development program incentives (or penalties).

LIFE CYCLE COST

In addition to these specific measurable items affecting LCC, we were required to develop, in conjunction with the Navy, an O&S cost model. Utilizing the model, periodic LCC reports are required. Further, LCC analysis is used throughout the program as a decision making tool in design tradeoffs.

So in summary, the key parameters affecting LCC are requirements placed on the F404 and these requirements have teeth, in the form of financial incentives and penalties.

DESIGN EVOLUTION

In this section, I will discuss some of the typical engine design actions/trade-offs, etc. that have occurred as a direct result of the emphasis on the above parameters affecting LCC.

General Electric management methods were discussed in some depth at the last seminar, so I will not reiterate except to outline briefly the four key features.

1). Individual goals were established at the detailed hardware level. Goals were established for reliability, weight, cost, maintainability, in addition to the more usual performance and durability requirements.

2). Establishment of individual goals was accomplished in conjunction with design engineering. With the aggregate goals in mind, Engineering managers could apportion goals among individual hardware items in such a way as to make them realistic and attainable.

3). Top management has been intimately involved through frequent and detailed reviews of hardware status. These reviews have exposed potential problem areas early, and the top management interest and commitment has provided the key decision making power and the necessary priority to see that problems were addressed early and solved. Top management attention has also supplied an important overall program perspective, particularly to those

items involving tradeoffs.

4). R&M, weight, and cost, in addition to performance requirements, were imposed on all major suppliers, particularly for supplier designed items. Ceiling price agreements have also signed with major component suppliers, to protect prices for the 520 DTC engines.

TYPICAL TRADEOFFS

- Combustor - Machined Ring vs. Sheet Metal

  This trade results in a higher acquisition cost, but reduced LCC due to greatly improved service life. In addition, this trade resulted in lower weight.

- Front Frame - Material Change

  The YJ101 Front Frame was a coated 410 stainless steel material. This material however, is susceptible to corrosion in a salt environment. Material was changed to Inco 718, at an increased acquisition cost, but lower LCC due to significantly improved service life.

- Outer Duct - Chem Mill vs. Honeycomb

  This part was changed from a steel honeycomb structure to chem milled titanium, with a substantial reduction in acquisition and spare parts cost and LCC, but in this case, an increase in weight.

- Alternate Source Programs

  In an effort to control costs of supplier hardware, "should cost" estimates are made by GE value engineers to compare against supplier quoted prices. In the case of several purchased parts where costs substantially exceeded "should cost" estimates, alternate source programs were established to create competition to qualify lower cost/technically superior alternatives. This effort increased development cost, but substantially reduced LCC via reduced production acquisition cost, and technically improved parts.

- Combustor Frame Locking Inserts

  The F404 specification allows no lockwire, except on parts that are serviced only at organization level. In general, however, lockwire has been avoided as much as possible to improve maintainability. At one location, however, this was making it necessary to use a high temperature, high cost self-locking insert. LCC analysis showed that the additional initial assembly, and downstream maintenance times were more than offset by the reduction in cost by reverting to lockwire at this location.

These examples are typical trades which have been made in an effort to reduce LCC. There have obviously been innumerable smaller order trades, as well as hundreds of changes which improved LCC by improving one or more of the contributing parameters without trading anything.

RESULTS

At this point, we are beginning the PFRT phase of the development program. Substantial engine test hours have been accumulated, allowing a good assessment of the results of the design emphases that have been discussed here.

Figures 3 through 5 are summary of the engine status to date. Most of the figures are self-explanatory. The DTC curve requires a bit of explanation. As can be seen, there has been an upward development cost adjustment since engine testing began in Jan., 1977. This was anticipated, as a result of hardware fixes dictated by engine test experience. Because of this planned adjustment, the aggregate hardware cost goal was to be at 5% below the DTC requirement as of the time of the first engine to test (FETT). The 5% margin was achieved, and planned adjustment has occurred since, with cost tracking very well at this time.

As the figures show, the overall results so far are very encouraging; we are confident that many goals will be substantially bettered.

LESSONS LEARNED

The following items are my observation of the particularly successful results to date in the F404 program, along with some suggestions for possible improvements for future development programs.

- Incentives Work

As we have seen, the incentivised F404 requirements are tracking very well, without exception. It is probably true that some requirements would be as good, or nearly so, in the absence of incentives. In my experience, however, the incentives provide at least an important stimulus. In some cases (eg: alternate source program), the financial return via future incentive provides a justification for additional effort and/or expenditure during development.

- Flexibility versus Goals

Nobody likes to miss any goals. If all requirements are better than their respective goals, effective tradeoffs can be made among the several requirements on an LCC basis. However, if one or more requirement approaches or exceeds its goal, there is a tendency to tradeoff in favor of improving the problem

requirement so as not to miss its particular goal. It is probable that such tradeoffs are not always the most effective from an overall LCC basis. For the future, it might be beneficial to establish individual goals which were not fixed, but rather subject to incentives/penalties based around a nominal value. A classic example of this phenomenon could be made with cost/weight tradeoffs. There are usually a large number of relatively simple tradeoffs that can be made at any time during a program. On an LCC basis, the impact of a dollar in acquisition cost can be easily determined. Likewise, with a pound of weight. Thus, the equivalence of cost and weight on a $/Lb. LCC basis can be determined. This figure could theoretically be used throughout the program as the tradeoff threshold. However, if weight is a problem (i.e, may miss goal) and cost is below goal, the tendency will be to change the tradeoff value in favor of weight reduction. If this happens, cost and weight could both meet goal, but LCC would be higher since it would have been better in this example to "overrun" weight and "underrun" cost.

Requirements Incentives Based on LCC Benefit

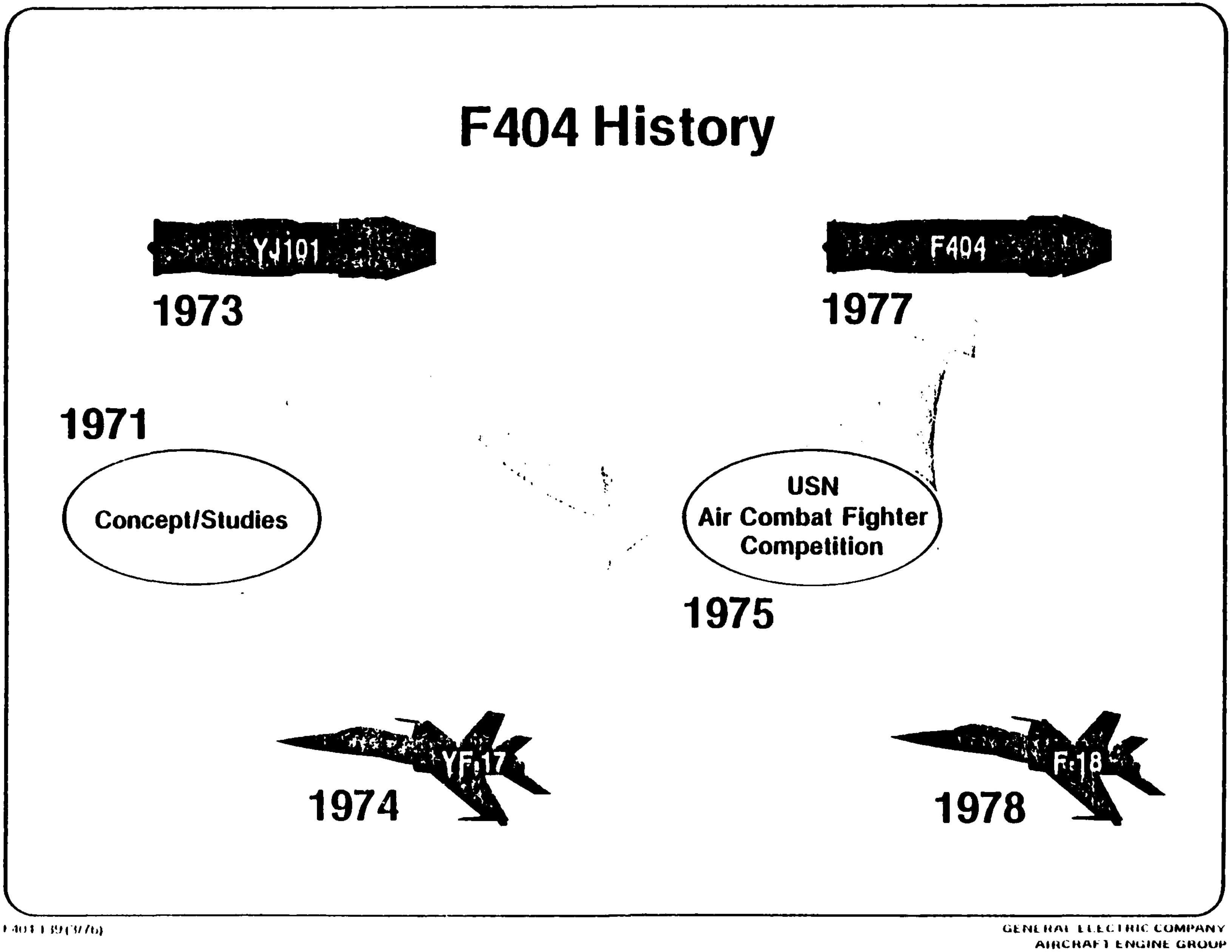
• All parameters, Reliability, Maintainability, Weight, etc., do not have the same impact on LCC. For example, a 1% improvement in reliability might be worth more or less than a 1% improvement in cost on an LCC basis. Contractual requirements for tradeoffs (or incentive schedules if incentives are being used) should be based on LCC payoffs. Thus, it might be okay if cost were overrun by 1%, provided that Reliability were bettered by, say, 1.5% or more (the numbers being determined by relative LCC payoff). Also, determination of the relative influence factors should consider the complete aircraft system.

Risk Protection in the Event of Long Range Payback

• In the alternate source programs I have mentioned, substantial development cost has been absorbed, based on anticipated payback via the DTC incentive in production. However, there is never any guarantee that long range production plans will happen, and if they don't (eg: if production were cancelled), there would be no payback. Some protection against loss in the event that the payback opportunity does not occur would make some of these choices easier.

Summary

• The YJ101, forerunner of the F404, was conceived in an achievement which was geared to simplicity and cost well before "LCC" became a key subject. This approach continued and in fact was greatly increased with the F404, including contractual requirements directed toward controlling LCC. Results to date are encouraging and we believe that the F404 will meet or better its commitments. For the future, some suggestions have been offered which might lead to better control of LCC leading to, perhaps contractual requirements for LCC itself.


F404 History
YJ101
1973
F404
1977
1971
Concept/Studies
USN
Air Combat Fighter
Competition
1975
YF-17
1974
F-18
1978
GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

(FIG. 1)

Engine Development

	Classical	F404
PFRT	Yes	Yes
MQT	Yes	Yes
Low Cycle Fatigue (Hours)	None	1,300
Operational Mission Testing ("SMET") (Hours)	None	2,250
Accelerated Service Testing (AST) (Hours)	None	2,000
Total Hours	10,000	*16,000
Duration (Months)	42-48	*71

*Includes AST

F404-219(11-77)

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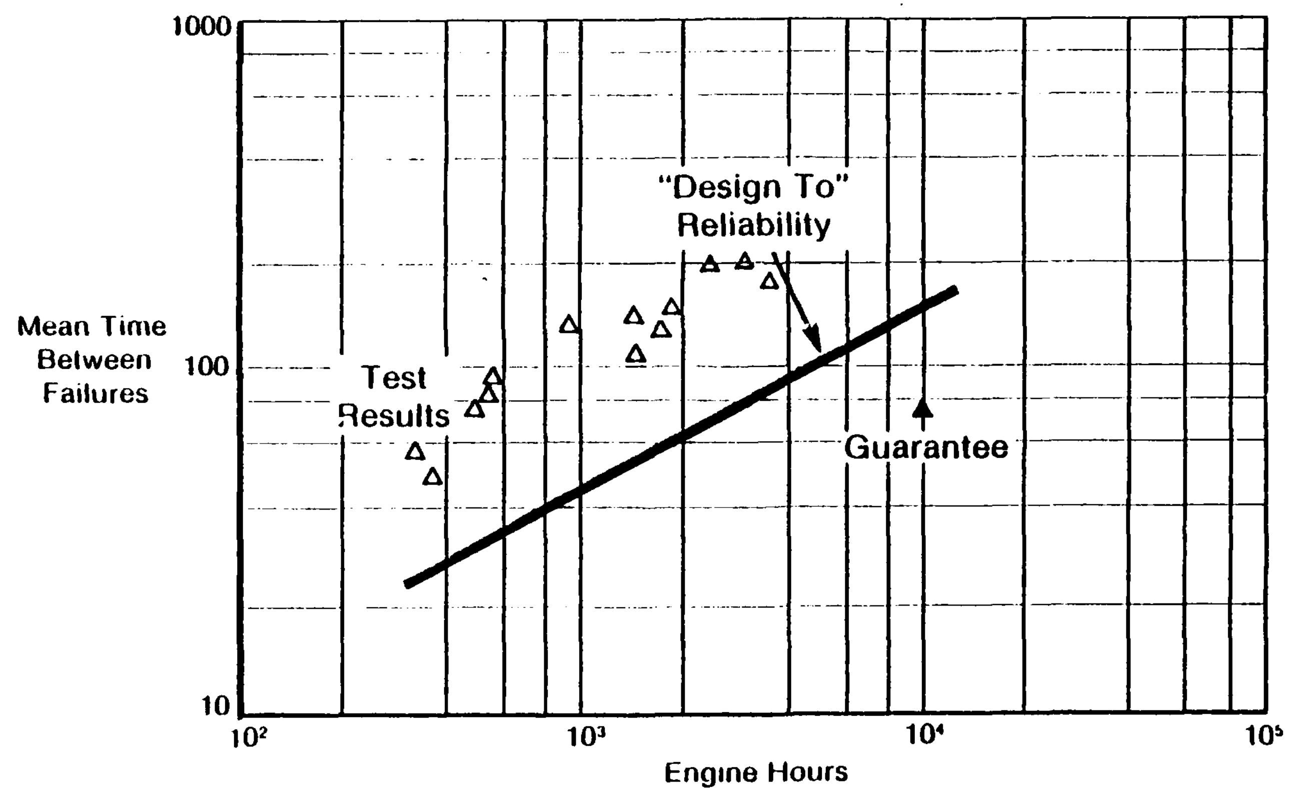
(FIG. 2)

F404—FSD Reliability Growth Goal



F404-331(4-78)

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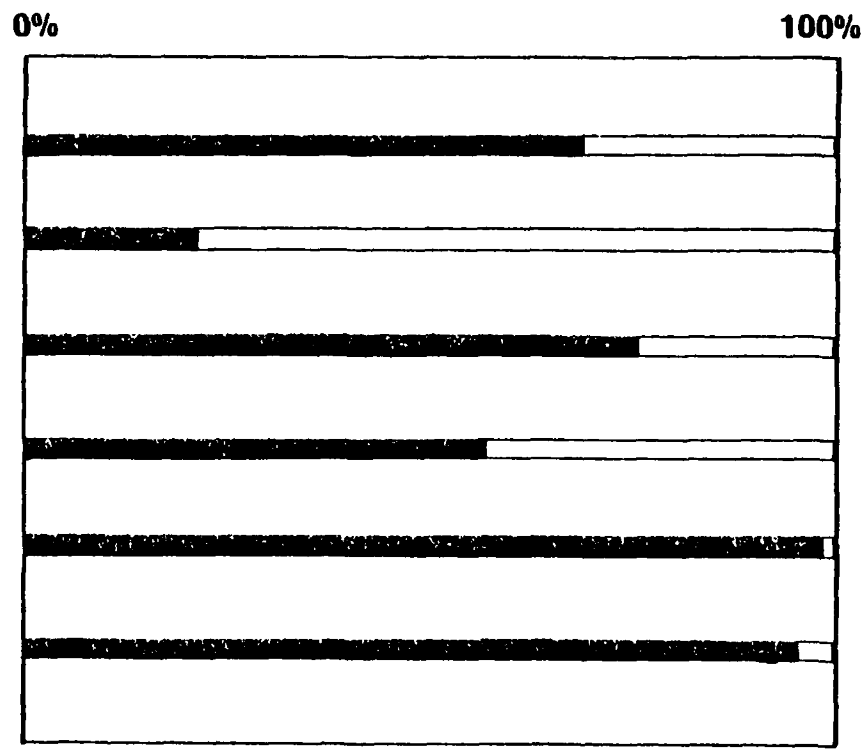
(FIG. 3)

Maintenance Measurements of AST

- MTTR (Hours/Eng)
  — Organizational Level
- Maintenance MH/Eng Hour
  — Intermediate Level
- Maintenance MH/Eng Hour
  — Depot Level
- Maximum Repair Time
  — (Hours)
- Replacement Parts Cost
  — ($/Eng Hour)
- Total Support Cost
  — ($/Eng Hour)



F404-480(4-78)

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(FIG. 4)

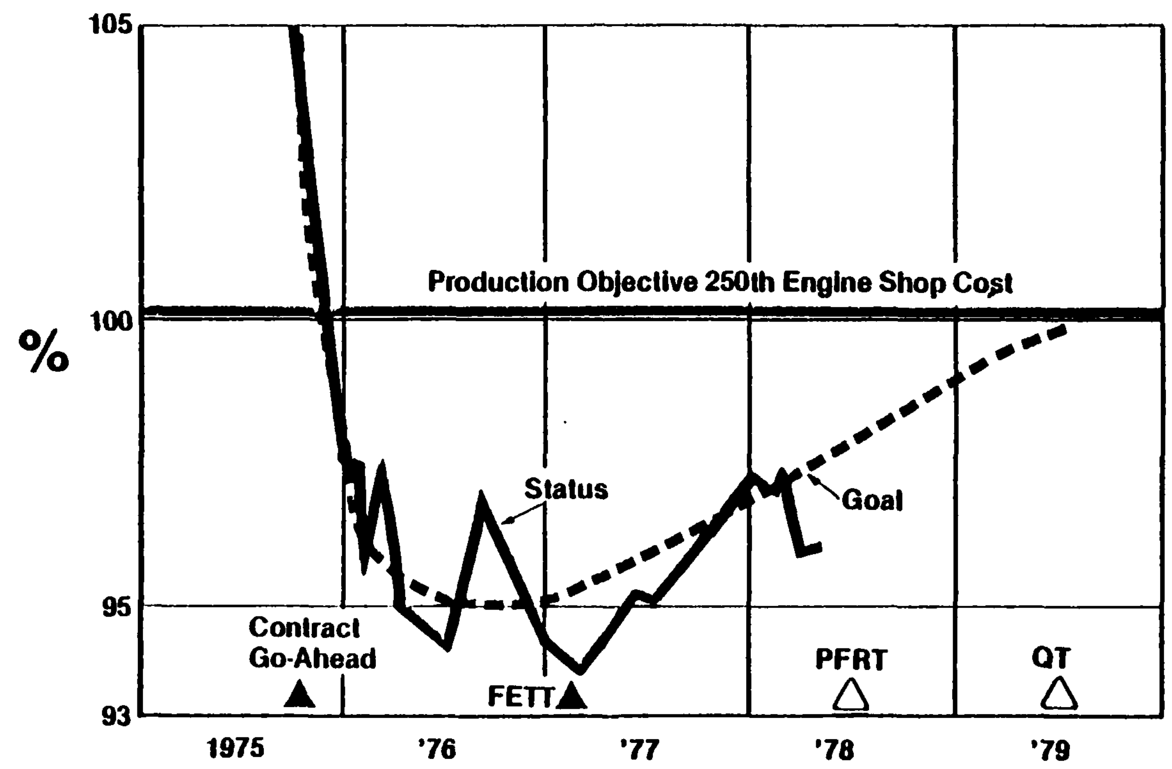
AD-A092 043 NAVAL AIR DEVELOPMENT CENTER WARMINSTER PA F/G 21/5
PROCEEDINGS OF OSD AIRCRAFT ENGINE DESIGN & LIFE CYCLE COST SEM--ETC(U)
1978 R M STANDAHAR, R R SHOREY, A PRESSMAN

UNCLASSIFIED NL

2 OF 2

AD A
092043

Design-to-Cost



F404-134(4-78)

(FIG. 5)

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AREAS OF LCC SAVINGS ASSOCIATED

with the use of

INFLIGHT ENGINE CONDITION MONITORING SYSTEMS

on

MILITARY AIRCRAFT

A paper prepared for the Office of Secretary of Defense Sponsored Aircraft Engine Design and Life Cycle Cost Seminar held at the Naval Air Development Center, Warminster, Pennsylvania - May 17-18, 1978.

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Introduction

The inflight monitoring of an aircraft engine condition status is a technique used since the first aircraft became airborne and the first pilots noted engine vibration levels through their "seat-of-the-pants" sensor package. Standard cockpit instrumentation which every pilot considers necessary to fly the aircraft is monitored to determine engine condition and often provides information which is trended to give indications of engine health and required maintenance actions. Inflight engine condition monitoring has indeed been around as long as aviation, but what is changing is the relative degree of sophistication of these monitoring techniques. As aircraft gas turbine engines become more complex and costly and as their maintenance and support costs increase; the need for more effective monitoring techniques becomes a necessity.

This paper will discuss the use of relatively sophisticated inflight engine condition monitoring techniques and devices and will attempt to relate their use to areas of benefits and life cycle cost savings associated with the ownership of an aircraft gas turbine engine. These inflight engine condition monitoring systems (IECMS) require data from a set of engine sensors; provide some degree of airborne signal conditioning; data processing and data analysis; activate cockpit warnings and/or health status indications and store data for post-flight detail analysis, fault isolation and trending. In recent years, several IECMS of varying degrees of sophistication have been developed, prototyped, evaluated and is some cases, implemented on military aircraft.

Some of these systems are listed in Figure 1.

FIGURE 1
AF/NAVY ENGINE CONDITION MONITORING PROGRAMS

- AV-8A/F402 (KOLLSMAN ELR)
  2 PARAMETERS - TURB CREEP
- AV-8A/F402 (PLESSEY EUMS)
  13 PARAMETERS - TURB CREEP, LCF, HIST. DATA
- TA-7C/TF30 (HOWELL JEM)
  PARAMETERS - PERF AND MAINT DATA
- T-38/J85 (NORTRONICS EHMS)
  23 PARAMETERS - COMPREHENSIVE SAFETY, PERF AND MAINT DATA
- F-18/F404 (MCAIR/BENDIX IECMS)
  23 PARAMETER - COMPREHENSIVE SAFETY, PERF AND MAINT DATA
- F-15/F-16/F100 (MCAIR/CONRAC EDS)
  47 PARAMETERS - COMPREHENSIVE SAFETY, PERF AND MAINT DATA WITH FAULT ISOLATION
- A-7/TF41 (TELEDYNE IECMS)
  51 PARAMETERS - COMPREHENSIVE SAFETY PERF AND MAINT DATA WITH FAULT ISOLATION

Older techniques of engine condition monitoring were almost never questioned as to their cost-effectiveness and were not considered as to their life cycle cost (LCC) impacts. As the newer engine condition monitoring devices bring together an increased number of systems elements, particularly avionics and software, their complexity and costs increases.

These increased acquisition and support costs coupled with added installed weight and the question of system reliability causes mandatory cost-effectiveness considerations to be reviewed for any new IECMS. This close review and scrutiny of developing IECMS will certainly be the rule until enough satisfactory experience is gained with a variety of these systems to establish a universally accepted policy for their application and benefits.

To date, there has been a wealth of experience with the use of engine condition monitoring systems on military aircraft. The obstacle to conclusive acceptance of the benefit of these systems has been that deocumentation of actual LCC savings associated with their operational use has been poor to mediocre. Several factors contribute to this lack of well documented LCC savings benefits, but the major cause seems to be inadequate definition of what the actual ownership costs are for any current military engine. Secondary causes for the inconclusive demonstration and documentation of specific LCC benefits seem to involve inherently poor military data retrieval programs, inadequately defined evaluation criteria, abbreviated tests involving too small a sample base and inability to quantify certain key benefits. Nevertheless, the sum total of experience to date has tended to support the conclusion that relatively sophisticated IECMS can offer significant LCC savings benefits to both current and new military aircraft engines. These benefits and areas of LCC savings associated with the use of IECMS on military aircraft will be identified in the subsequent discussion.

Operational Systems Experience

The U.S. Navy has had a great deal of experience with a sophisticated engine condition monitoring system called the A-7 IECMS on the TF41-A-2 powered A-7E aircraft. The development of the A-7E IECMS has followed a comprehensive and well scrutinized T&E (Test and Evaluation) program dating back to 1971 and culminating in a VA-27/97 ten aircraft preproduction fleet technical evaluation followed by a production configuration operational evaluation during two subsequent U.S.S. Enterprise deployments, Sept 1974 to April 1975 and Aug 1976 to Mar 77.

The A-7E IECMS is a system for engine condition monitoring to detect impending engine and component malfunctions that could result in the loss of aircraft or mission abort. The IECMS was designed to define current engine health status and to automatically indicate the necessary corrective maintenance actions. In addition to being a safety-of-flight indicator, the IECMS has the potential to improve aircraft availability by reducing engine related maintenance downtime, simplify engine troubleshooting by maintenance personnel and reduce engine logistic support costs by support of an "on-condition" maintenance concept.

The A-7E IECMS consists of three major elements that perform the following functions:

a. An AIRBORNE UNIT - which continuously monitors 51 engine and airframe parameters and automatically records a minimum amount of flight data on a removable tape cassette. This unit also activates cockpit lites as a warning of potential safety-of-flight problems and

trips exceedance status flags for post-flight inspection.

b. A SENSOR PACKAGE - which consists of an engine harness and 31 added engine transducers, picks up and discretes switches.

c. A GROUND STATION - which analyzes recorded flight data to perform engine health status diagnosis and to automatically report maintenance action requirements. Data output from this unit is also used for engine trending.

The IECMS performs its functions as an indicator of safety-of-flight and engine health status through a number of diagnostic logic computer saftware routines. These routines include the following:

a. Limit Exceedance - which continuously compares critical engine parameters against established operating limits.

b. Gas Path Analysis - which continuously compares current internal engine health against an established individual engine performance baseline signature.

c. Vibration - which continuously compares current engine vibration frequency levels against an established individual engine vibration signature.

d. Oil Quality - which continuously monitors the amount of foreign particles in the engine oil to give the pilot a real-time warning of deterioration in the engine lubrication system.

e. Accessories - which continuously monitor engine component subsystems such as the main and manual fuel controls, temperature and overspeed limiters, fuel pumps, ignition and generator, inlet guide vane control, and automatic relite actuators.

To date, the A-7E IECMS has demonstrated operational capability both ashore and in carrier based environments with over 18,000 flight hours achieved. The IECMS has shown good reliability and has demonstrated its usefulness as a maintenance tool which can automatically indicate actual and impending engine discrepancies. Figure 2 presents some of the typical valid diagnostic "finds" indicated by IECMS during operational use.

FIGURE 2
TYPICAL A-7E IECMS DIAGNOSTIC "FINDS"

HP Turbine Blade Failures	Overspeeds Limitations
HP Compressor Seal Rub	Overtemperature Limitations
HP Compressor FOD	Fuel Control Adjustments
LP Cooling Air Tube Failure	Governor Adjustments
Distressed HP Turb Blades/Vanes	Limiter adjustments
CSD Mounting Bracket Loose	Failed Fuel Controls
LP Compressor Balance Bolt Failure	Failed TLA
Non-Integral Vibration Indicated	Failed Airflow Regulators
NARF Assembly Rotor Unbalance	Failed Fuel Pumps
Ignition System Problems	Wrong T5 Ballast Resistor
Pressure Leaks	Sensor Transmitter Failed
Cockpit Indicator Problems	Bad Start Carts
Oil Filter Blockage	Operational Procedures

The A-7E IECMS preproduction and early production configuration operational experience has indicated that the system can perform its design functions and does offer significant safety and maintenance benefits.

The IECMS will detect and diagnose safety-of-flight engine malfunctions resulting in potential aircraft saves. Numerous IECMS indicated maintenance "finds" before normal maintenance procedures indicated a problem, have been documented as valid. Several unnecessary engine removals were prevented. Various squadron reports state that the A-7E IECMS has been a valuable diagnostic tool aiding them in their routine maintenance troubleshooting. A Naval Aviation Integrated Logistic Support Center (NAILSC) assessment of IECMS cost-benefits, Report No. NAILSC 200-76-01 of 15 February 1976, made the following conclusions about the IECMS equipped engines operational experience:

a. Lower engine removal rate - 18% reduction.

b. Shift of repair action to lower maintenance levels.

c. Lower average cost per repair at AIMD or above maintenance level - 14% reduction.

d. Reduction in secondary engine damage.

Presently, production configuration IECMS hardware is being flown in conjunction with the TF41 LTF (Lead-The-Fleet) evaluation being conducted in VA-46/VA-72. Beside being used as a daily maintenance tool, the IECMS is generating data on mission profiles flown, documenting engine operating procedures and hot section usage, and providing trend data on engine performance degredation with time. This engineering data has been extremely valuable in verifying particular failure modes and documenting engine operation history in respect to the status of the LTF hardware under evaluation. To date, the sum total of the operational reports indicate that the IECMS has successfully demonstrated

its potential as a safety-of-flight indicator and as an effective maintenance tool, and has provided continuous and valuable engineering data.

Data and experience generated from the continued evaluation and operational use of the A-7E IECMS has led to a series of conclusions supporting the identification of potential areas of LCC savings associated with the use of engine condition monitoring systems on military aircraft. This operational experience coupled with other general analytical cost-effectiveness studies (e.g. Air Force Turbine Engine Monitoring Systems Report, TTCP Technical Report HAG-2-77 on Military Gas Turbine Engine Health Monitoring, SAE E-32 Committee on Aircraft Gas Turbine Engine Monitoring) and IECMS design trade study results on the F-18A/F404 and AV-8B/F402 aircraft development programs, have led to conclusions as to the areas of benefits of an IECMS on military aircraft gas turbine engines. The predicted areas of LCC savings benefits impacted by the use of IECMS are defendable and justifiable from both actual operational experience and from carefully conducted analytic cost-effectiveness studies. Though the predicted areas of LCC saving benefits can and have been identified, accurate levels of savings have not yet been quantified either from actual experience or with analytic studies. The following discussion will deal with defining these areas of benefit but will not attempt to predict actual quantitative levels of LCC savings.

Benefit

There appears to be three broad categories of LCC cost savings associated with the use of IECMS on military aircraft engines. These categories are in the areas of operational, maintenance, and logistics benefits. Cost-effectiveness considerations aside, there seems to be general agreement that significant benefits can be achieved within these categories. The relative degree of these benefits will, of course, depend on the scope and complexity of the engine, aircraft and IECMS involved. Whether the sum total of these benefits warrant the acquisition and support costs for having an IECMS, is the subject of LCC trade studies for each individual engine/aircraft application. Nevertheless, the usage of an IECMS on military aircraft, particularly high performance tactical aircraft, can generally be expected to achieve the following areas of benefits:

a. Reduced aircraft attrition rate through real time cockpit warning and post-flight diagnostics of potentially catastrophic engine events.

b. Increased mission reliability and operational readiness through the reduction of mission aborts and improved turn around times.

c. Increased maintenance effectiveness and procedures resulting in reduced troubleshooting times and maintenance costs.

d. Reduced maintenance and material usage through early fault identification, a decrease in false removals and reduction of secondary damage.

e. Improved data feedback to the engine designers and managers

resulting in early engine maturity and more effective use of product improvement resources.

f. Reduced logistics support costs.

g. Reduced fuel usage through decreasing ground troubleshooting runs and early detection of engine deterioration.

Any IECMS will attempt to impact benefits in the above-mentioned areas of potential LCC savings. How well a particular system might achieve these predicted benefits depends on system's design and the specific "needs" a certain aircraft/engine combination has in its mission application. It is felt that in developing a particular IECMS design, certain functional capabilities must be thoroughly considered if the above-mentioned areas of benefits are to be achieved for any specific application. It should be noted that desired functional capabilities may provide benefits in several over-lapping areas. There may be additional functional capabilities desired for some specific application, but the following should be considered as a minimum for any application:

a. <u>Safety-of-Flight Monitor</u> - Incipient failure indications should be provided with real-time cockpit warning and/or ground analysis between flights. For those problems that the system can be effectively designed to address, timely pilot warning will be provided to permit inflight response to discrepancies seriously affecting flight integrity or leading to catastrophic engine failure. This function could also be considered an indicator for incipient mission abort situations.

b. Pre-Flight/Inflight/Post-Flight Status Monitor - Indications could be provided to the cockpit to support pre-take-off check list type items (e.g. Thrust check at take-off) and GO for flight status. Similarly, post-flight GO/NO GO status indications should be provided to determine whether the aircraft is "up" for the next flight.

c. Maintenance Diagnostic Features - Indications shall be provided for post-flight determination of engine health status to aid in ground maintenance decisions. A general indication of limit exceedances and gross problem areas will be required for immediate post-flight inspection. A flag or bit status panel could be used for general limit exceedance and problem area indications while particular diagnostic indications to fault isolate to a LRU (Line Replaceable Unit) or component level could be accomplished with some type of data processing ground station (DPGS). Problem detection to a particular problem definition should be provided as a minimum, with fault isolation to the LRU, component, or lower (more detailed) as justifiable by failure modes and effects analysis (FMEA), MSG-2 type analysis, and cost-effective analysis trade-offs.

d. Performance/Trend Monitoring - Indications shall be provided to identify degradations of engine gas path performance and to support both short-range and long-range trending techniques. Individual engine performance signature identification should be supportable and could be used as a base of trending techniques. Similarly, the capability to support installed trim check techniques is desirable. Performance

trending, sometimes known as gas path analysis, will be used at the operational level as a step or signature change indicator to identify engine discrepancies associated with FOD, component efficiency deterioration, low thrust, and control system scheduling. At higher maintenance levels, performance trending will be used to track gradual changes in engine performance signatures to indicate when an overhaul is required.

e. Life Usage and Mission Profile Analysis - Indications shall be provided to track how the engine is operated or handled on any particular flight. Similarly, the capability shall be provided to record and bookkeep the accumulation of significant life usage events over the complete service life of the engine. This could be accomplished by the measurement and accumulative recording of significant events, parameters, speed, stress, and thermal cycles. Life usage data would be used to support LCF analysis, thermal fatigue and creep analysis, and critical parts life used determination. Life usage data would enable individual engine components to be "lifed" based on actual use rather than some arbitrary time limit. Mission profile data would enable informed management decisions to be made on changes in operational usage of complete engine fleet. This data would enable more effective engine testing to be accomplished and would aid logistic support in planning for spare and replacement components.

f. Data Retrieval Features - The capability shall be provided to record and store significant parametric data to support engineering analysis, long-range trending and provide inputs into the engine product support program (PSP). At the operational level, this data retrieval most likely will be limited to exceedance time history and event

documentation. At higher maintenance and managerial levels, these data retrieval features will be used to more effectively allocate logistics support resources and PSP funding.

g. Configuration Control and Histroical Record Keeping - As appropriate, capabilities shall be provided to record and track engine log book type information and actuarial data. These capabilities would be used to define and identify individual engines, accessories, modules, and ECP configurations. In order to provide effective engine condition monitoring capabilities, accurate engine configuration records must be maintained. The automation of engine configuration and acturial records not only supports other engine condition monitoring functions but also can provide accurate and timely feedback to a service wide engine accounting or management information system.

The previous listed desired functional capabilities should not be considered limiting. Additonal functional capabilities could be considered desirable when addressing unique problem areas associated with specific engine types and applications. These mentioned functional capabilities are in the general case, desirable for consideration in any engine application to achieve significant LCC saving benefits. Associated with and supporting these functional capabilities is a group of required diagnostic techniques and software routines. The general classification of some of these major diagnostic techniques and software routines can be considered as follows:

a. Limit Exceedance Documentation - To provide automatic monitoring and record keeping of all limit exceedances of critical operating

parameters (e.g. overtemperature, overspeed). Those parameters which would constitute a safety-of-flight circumstance if exceeded should be included in a cockpit warning presentation. Significant exceedance events would require time history documentation for improved maintenance troubleshooting.

b. Vibration Analysis - To provide automatic monitoring and analysis of vibration levels of pertinent engine rotating components for exceedance limits and vibratory fault signatures. In some cases, the analysis required would involve tracking changes in vibration frequency signatures. The vibaration analysis techniques would be used to detect rotor unbalance and bearing discrepancies.

c. Gas Path Analysis - To provide adequate gas path parametric data to support analysis of the engine and/or component performance condition. Gas path analysis techniques would be used in performance trends monitoring and to permit detection and isolation of engine discrepancies to the component or LRU level.

d. Oil Quality Analysis - Where appropriate, to provide indications for the analysis of both the quantity and quality of the engine lubrication system. This analysis could range from relatively simple oil levels and pressures, to ground based SOAP or ferrographic investigations to real-time airborne oil quality indications.

e. Accessory Diagnostics - To provide adequate data and fault tree logic for analysis of the condition status of significant engine mounted accessories. Those engine accessories to be monitored will be indicated by FMEA and MSG-2 type analysis as being high maintenance

drivers and/or flight safety critical. The use of additional parameters strictly for accessory diagnostics will, in most cases, be difficult to justify. Effective accessory diagnostic routines would greatly improve operational level troubleshooting efficiency.

f. Data Validity/Self-Check - To provide continuous self-check features which would ensure the integrity of sensor signals, hardware and software. Adequate software logic should be provided to establish the validity of input data. Effective data validity and self-check features will maintain a high degree of valid diagnostic outputs and user confidence.

It has been the declared goal of most military maintenance organizations to work towards the on-condition maintenance (OCM) concept and away from arbitrary fixed overhaul lives which are wasteful and ineffective. To implement effectively a full OCM capability, ground maintenance personnel must be provided with reliable data on engine condition and health status, life usage, performance trend information. Though not the only means of providing this data, IECMS are geared to most conveniently provide this capability.

Regardless of the aforementioned functional capabilities and supporting diagnostic techniques designed into a engine condition monitoring system, to achieve full LCC savings benefits, the system must be compatible with the maintenance concept established for the particular application. The design of the IECMS must be commensuate with the intent of the particular maintenance concept and the associated maintenance plan must consider integrating within it the function capabilities provided by an IECMS. Diagnostics and engine monitoring can be an attractive tool

to assure maximum aircraft mission availability at minimal life cycle costs through the practice of OCM. To be fully effective, the IECMS must supplement the other assessment techniques established by the maintenance plan to confine maintenance to that required for established cause only.

There seems to be two problem areas associated with the interface of IECMS with maintenance concepts. The first is the interface of an IECMS with an existing maintenance concepts have evolved over the life of an aircraft/engine by necessity rather than by planned intent. A maintenance plan thus evolving is not necessarily the most cost-effective technique of maintenance. If an IECMS is to be applied on a retrofit basis, then it must show improved cost-effective advantages. It must first successfully demonstrate its operational effectiveness and reliability before indicated changes in maintenance procedures can be implemented.

The second case involves the interface of an IECMS with a developing maintenance concept on a new aircraft/engine program. In most new aircraft/engine development situations, the IECMS system will be defined and in development before the maintenance concept and resultant maintenance plan are finalized. If an IECMS is to be fully operational on the first production aircraft, then the IECMS development cannot wait for the maintenance plan to be fully defined. To successfully develop the most cost-effective IECMS for any new aircraft/engine application, a continuous exchange of potential system capabilities with maintenance concept requirements must be accomplished throughout the development and initial implementation phases of the program.

Concluding Remarks

It is generally accepted that effective and reliable engine condition monitoring systems are within the realm of technical feasibility and indeed serve a valuable role in flight safety, maintenance, and logistics support aspects of military aircraft gas turbine engines. It can be stated that there are predictable and identifiable areas of LCC savings associated with the use of an IECMS in the operational environment. Though the benefits associated with the use of IECMS are real, these systems should not consider a panacea for all engine maintenance, logistics and other cost ownership problems. In the contemporary economic environment, the addition of an IECMS to a military aircraft must provide a significant positive cost benefit. The exact magnitudes of the predicted LCC savings benefits are not generally known for any specific application and must be subject to individual cost-effective and system design trade studies. Using the approach of considering all the predicted areas of potential LCC savings benefits and designing a system to take maximum advantage of those benefits needed for an individual application, cost-effective IECMS can be implimented to significantly reduce the ownership costs of military gas turbine engines.

MILITARY AIRCRAFT ENGINE LIFE CYCLE COST FROM A COMMERCIAL VIEW

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I. INTRODUCTION

The commercial marketplace has shown that it thrives on things certain. Things uncertain introduce doubt, anxiety, loss of profit, danger, and a general negative feeling. A positive approach is far easier to follow where the business conditions are understood and have well defined dimensions. The military operational situation closely parallels the commercial one in that uncertainty remains a major management challenge. There is a need to manage assets to reduce uncertainty and to reduce Life Cycle Costs. This paper will discuss the means used to achieve this purpose in the commercial world and suggests similar operating methods aimed at reducing military operations costs. The example used is a helicopter turbine engine.

II. BACKGROUND

The Model 250 series engine is known as the T63 in its military application. This engine began as a 317-shaft horsepower engine and grew through 400 horsepower to 420 horsepower. The 420-horsepower unit is designated as the T63-A-720 and is used in the Army OH 58C. The early T63 engines remain at 750 hours time-between-overhaul (TBO), while their civilian counterpart grew to 1500 hour TBO.

The commercial 250-C18, 250-C20, and 250-C20B have modular maintenance features. Operators owning 15 or more aircraft nearly always take advantage of lower direct operating costs usually associated with modular maintenance. The U.S. Navy[1]* takes advantage of turbine helicopter modular maintenance. The U.S. Army has shown little inclination to do so for T63 engines in peacetime.

*Superscript numbers refer to the references listed at the end of this paper.

III. COMMERCIAL PRACTICE

It is generally conceded that the turbine engine is 20 to 25% of a helicopter's flyaway cost. Therefore, the engine acquisition cost elements and operating costs should be understood.

The Model 250 (or T63 military designation) engine cost can be divided as shown in Figure 1. In the commercial sense, the importance of this cost distribution is usually seen only in the form of spare parts value. The helicopter manufacturer seldom shows the selling price of the basic airframe in its component form. The buyer sees the airframe price with engine(s) installed.

The operating costs become the next problem facing the helicopter operator. Figure 2 shows typical operating cost categories in percentages exclusive of crew costs. Many methods have been used for calculating operating costs, although some appear not to apply to rotary wing aircraft.[2] In any event, costs are usually divided between fixed and variable ones. The example shows 40% fixed costs. It also shows the engine maintenance being 23% of total costs or over one-third of variable costs. In addition, engine performance characteristics are a principal driver for fuel and oil costs.

Commercial operators must have revenue to offset costs to survive. Table I lists three interrelated functions necessary to provide for revenue (aside from paying customers). A well developed maintenance capability with adequate spare parts support is a must to achieve a high degree of aircraft availability. Today's customer usually has several choices available to do his travel. If your aircraft is not ready, then brand "X" down the street may be.

A simple example of a modified break-even chart is shown in Figure 3. The line identified "Savings" is usually shown labeled "Revenue." The divergence of "Savings" over "Variable" plus "Fixed" costs represents the profit (or loss) that can be impacted by more efficient, lower cost maintenance. The common factor is achieving safe operation at lowest cost and highest aircraft availability.

The next step is to trade off maintenance concepts from a cost standpoint (Table II). Maintenance plans impact both fixed and variable costs. Complete engine, on nonmodular, maintenance usually requires a smaller storage area than modular maintenance concepts. Modular maintenance usually enjoys superiority in every other respect.

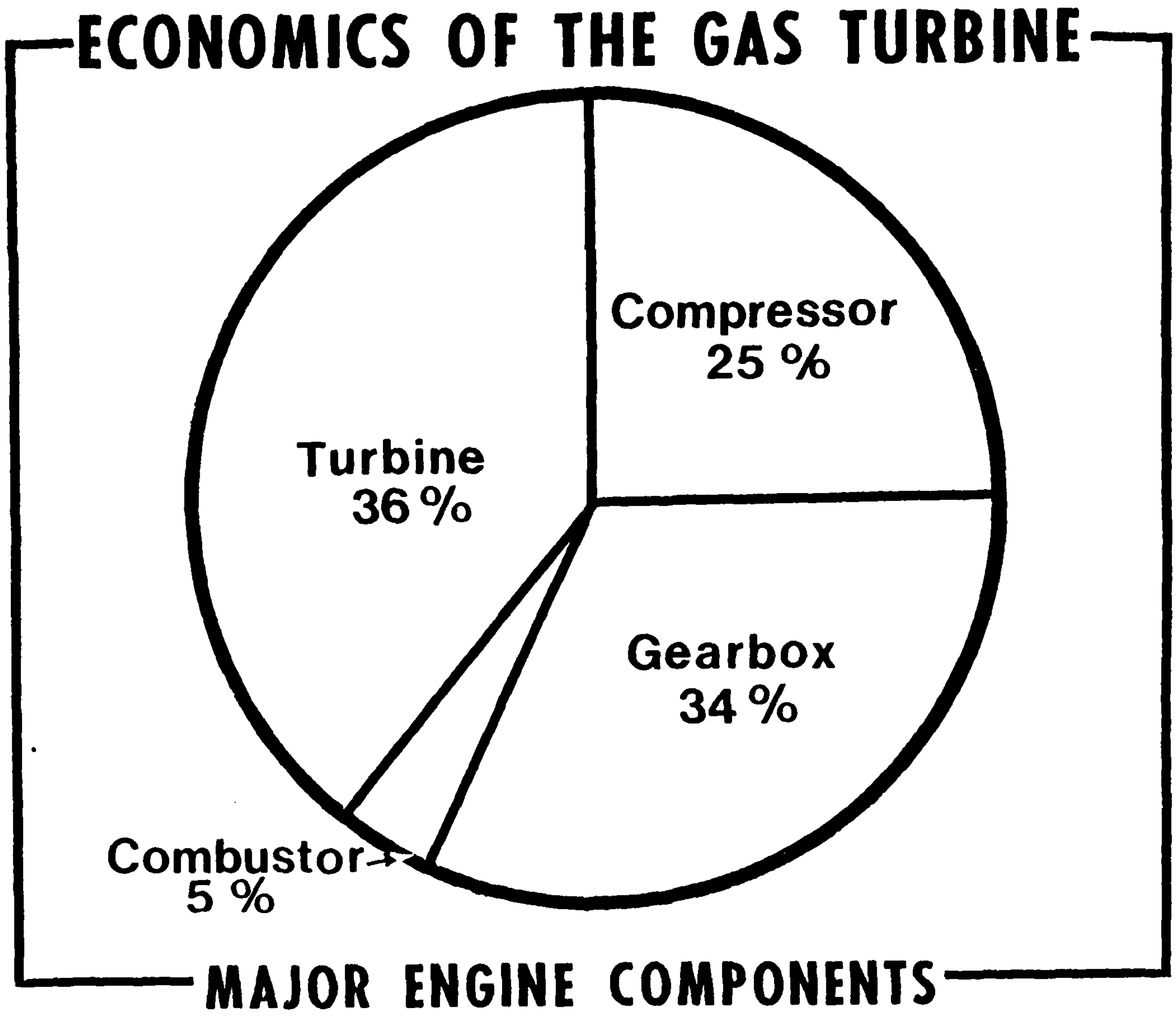
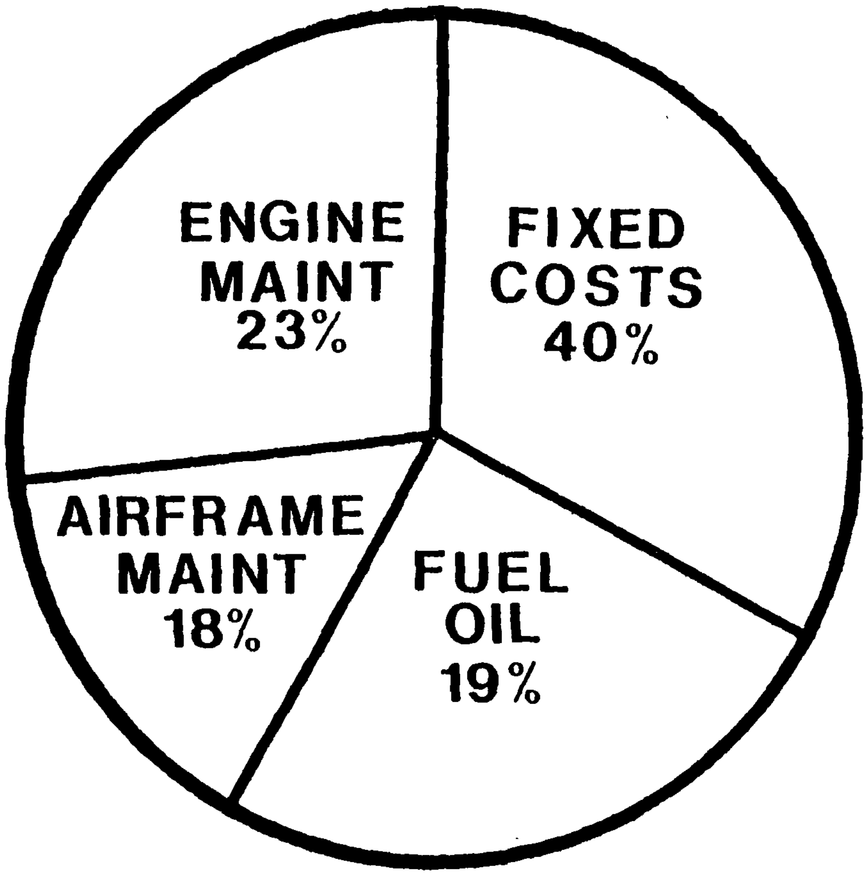


Figure 1. Major Engine Component Cost Percentages



LIGHT HELICOPTER
SINGLE TURBINE ENGINE
800 HRS YEAR
CREW COSTS OMITTED

Figure 2. Operating Cost Allocation

Table I. Elements Needed to Generate Revenue

REVENUE GENERATION

- AIRCRAFT AVAILABILITY
- MAINTENANCE CAPABILITY
  - SHOP & EQUIPMENT
  - TRAINED/CERTIFIED PEOPLE SKILLS
- SPARES INVESTMENT

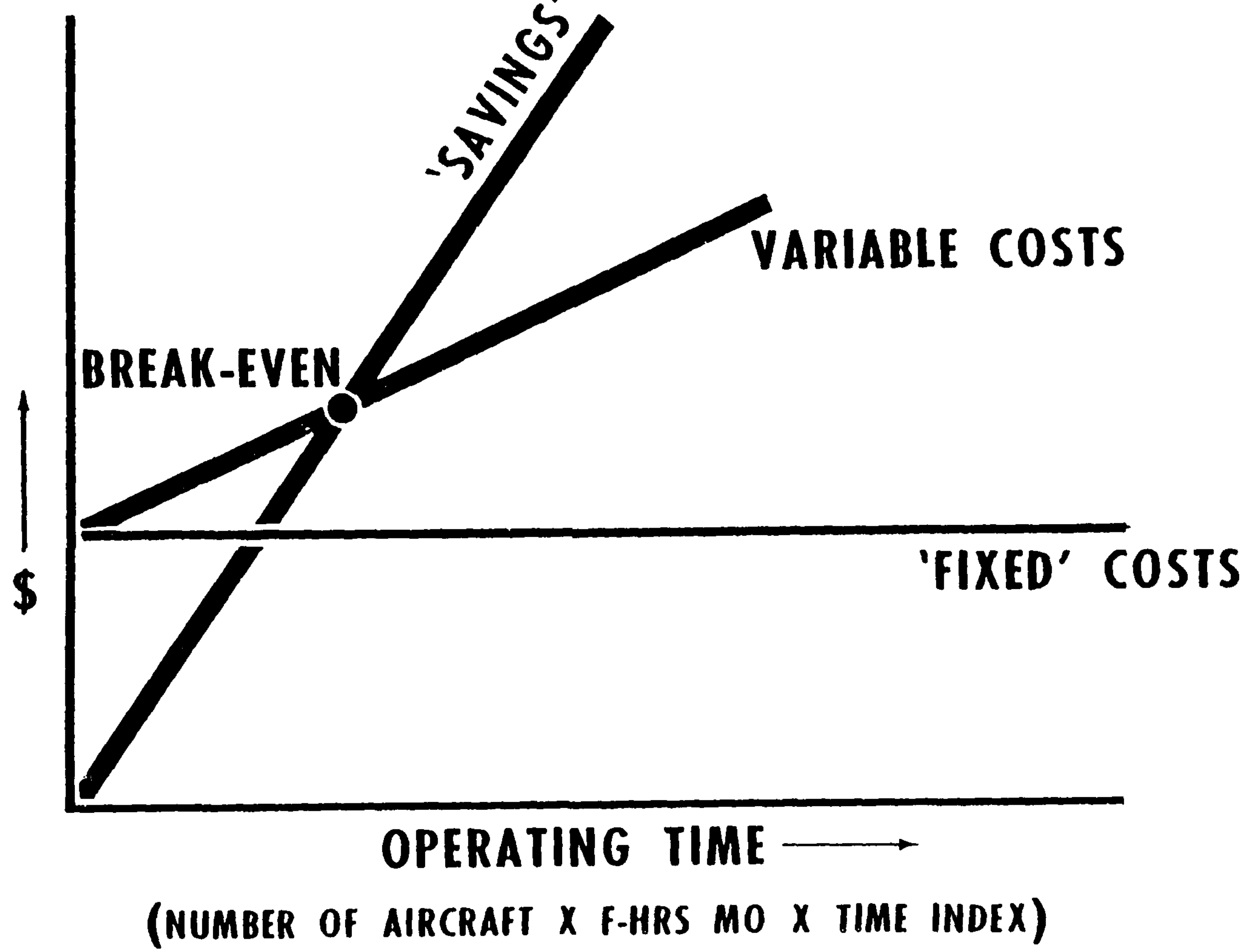


Figure 3. Break-Even Chart

Table II. Maintenance Plan Options

COST DRIVERS

- MAINTENANCE PLAN
    - COMPLETE ENGINE MAINTENANCE
    - MODULAR ENGINE MAINTENANCE

More specific considerations for trading off between maintenance plans are given in Table III. The term Unit Exchange describes trading a unit needing repair or overhaul and money for a new or reconditioned unit. The term Custom Repair describes the act of having one's own unit repaired or overhauled and returned for service. Complete engines usually cost more to stock as spares than selected modules for the fleet sizes addressed earlier. Less investment, therefore, is required to support aircraft availability when modular maintenance is used.

An added saving because of the maintenance concept is probable. It is usually less expensive to repair an owned engine module than to buy a unit exchange module. The penalty that must be recognized is repair time. A spare module pool becomes necessary which means that pool costs must be recognized.

CAUSES OF ENGINE MAINTENANCE

Engine maintenance generally falls into two categories—scheduled and unscheduled. Engine maintenance allocations are further expanded in Figure 4. The overwhelming cost element is overhaul reserve. Only about 4% of the engine maintenance direct operating cost is chargeable to unscheduled removals. The most potential cost reduction area happens to be affected by modular engine maintenance. Whole engine concepts are tied to the lowest module TBO. Modular engine concepts can take advantage of varying module TBO values. For example, a recent module TBO extension reduced projected Model 250-C20 operating costs over 10%.

Engineering effort has been directed toward other life limiting parts/assemblies to allow FAA approval for more life extension of Model 250 series engine modules.

IV. MILITARY RELATIONSHIPS

The military generally has a three-level maintenance concept. Aircraft engines sometimes enjoy a fourth level of maintenance. This fourth level, called Complete Engine Repair or Jet Engine Intermediate Maintenance, will be excluded from this review.

The U.S. Army three-level maintenance concept and capabilities are listed in Table IV. Examination of this table shows that the emphasis for repair is toward higher level (Depot) maintenance. Minimum fault isolation and work beyond line replaceable unit (LRU) exchange is contemplated. There are few ship replaceable units (SRU) planned at AVIM. Extensive engine repair and overhaul is accomplished at the Depot level.

Table III. Maintenance Plan Trade-Off

RELATIVE TRADE-OFF POTENTIAL

	MODULAR ENGINE	WHOLE ENGINE
DOWN TIME	LESS	CURRENT LEVEL
ROTABLE SPARE	LESS EXPENSIVE	MORE EXPENSIVE
FAVOR UNIT EXCHANGE		YES
FAVOR CUSTOM REPAIR	YES	

ENGINE MAINTENANCE

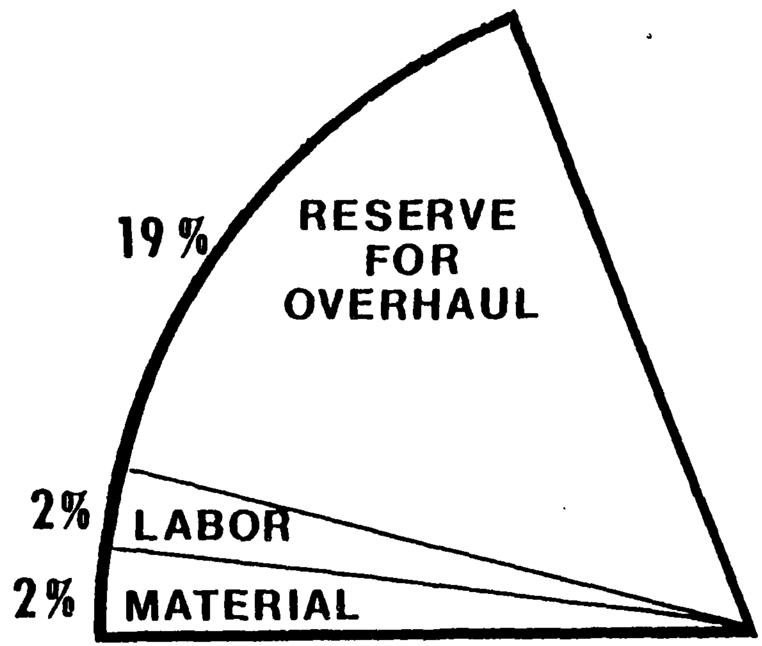


Figure 4. Engine Maintenance Allocation

Table IV. Army Three Level Maintenance Concept

ARMY THREE LEVEL MAINTENANCE CONCEPT

AVIATION UNIT MAINTENANCE (AVUM)

- NO SPECIAL TOOLS
- ON WING REPLACEMENT OF LRUs AND ENGINES
- FAULT ISOLATION TO LRU AND ENGINE LEVEL ON WING
- TWO AVUM SUBLEVELS (CREW CHIEF/AIRCRAFT REPAIRMAN AND LIMITED SHOP SUPPORT)

AVIATIATION INTERMEDIATE MAINTENANCE (AVIM)

- NO SPECIAL TOOLS
- LRU AND ENGINE REPAIR (MODULE REPLACEMENT)
- FAULT ISOLATE TO ENGINE MODULE LEVEL
- TWO AVIM SUBLEVELS (DIVISIONAL AND NONDIVISIONAL)
- ENGINE TEST STAND (METS) LOCATED AT NONDIVISIONAL AVIM

DEPOT

- MINIMUM NUMBER OF SPECIAL TOOLS
- REPAIR MODULES AND SELECT LRUs

The commercial maintenance approach is essentially a three-level one. Depending on the size of the business, unit maintenance and intermediate maintenance may be accomplished at one physical location. However, there are generally three functional levels: operator, fixed base operator (FBO), and distributor. The corresponding commercial and military maintenance levels are given in Table V.

The commercial maintenance emphasis is toward the operator. An operator will usually have some special tools and, perhaps, diagnostic equipment to work on a larger range of LRUs. The FBO usually does repair of LRU and many SRUs. Some major operators have complete engine repair capability except for doing zero-time overhauls. The extent of capability varies with the number of engines to be supported. The more engines owned, the more repair capability is usually afforded.

V. CONCERNS

Accounting practices vary from military to commercial users. However, this paper will not address this subject. Observations are confined to maintenance, operation, and support differences.

There are three principal concerns:

1. Military TBO
2. Modular maintenance
3. Level of repair

Experience with the T63 and its civilian counterpart, the Model 250-C18, indicates more economical life built into the engine than is extracted by the military.

The T63-A-720 appears to be going along a similar trend. The Model 250-C20 and Model 250-C20B both have more TBO capability than appears to be targeted in the military application. From a commercial standpoint, TBO extension helps reduce the reserve for overhaul which is the largest single maintenance cost contributor for current engines. (See Figure 4.) Of course, TBO must be traded with premature removal rate to achieve a balance between operational readiness and cost.[3] Generally speaking, the highest TBO without sacrificing safety is the most economical maintenance plan.

Table V. Military/Commercial Maintenance Levels

MILITARY/COMMERCIAL MAINTENANCE LEVELS

MILITARY	COMMERCIAL
AVIATION UNIT MAINTENANCE	OPERATOR
AVIATION INTERMEDIATE MAINTENANCE	FIXED BASE OPERATOR
DEPOT	DISTRIBUTOR

Modular maintenance is another way to extend engine life and lessen overall cost. The Model 250-C18 used by the USN[1] is supported under a modular maintenance plan. Costs were lowered at no loss in operational readiness when modular support was adopted in mid-1976. Typical TBO values for a current mature engine, the Model 250-C20, are shown in Table VI. A substantial reduction on overhaul reserve is available to both commercial and military users. The commercial community is taking advantage of the operational savings.

When enough engines are owned by an operator, the opportunity to assemble near remaining time modules together in one engine arises. This technique has allowed some large operators to safely extract over 96% of module TBO life.

Level of repair emphasis at user or FBO saves money if there is sufficient investment in tools and facility available. One corporate fleet which operates two twin-engine turboprop aircraft has found it cost effective to buy special tools which allow certain power turbine repairs on-wing. A commuter airline operating two twin-engine turboprops has found it profitable to invest in capability to do even more work in his shop. Both of these examples are probably able to enjoy this economic advantage because of low turnover of capable, trained mechanics. A cursory review of refurbishment price lists shows a cost advantage for forward as opposed to depot maintenance.

VI. SUMMARY

The commercial world, under pressure from the marketplace, has led the way toward economic operations. The military has the challenge of reviewing its needs and assets which may allow an improvement in operating and maintenance costs.

There is probably no revolutionary change coming in maintenance concepts for helicopter turbine engines. Engine health monitoring devices may assist in detecting incipient failure and in diagnostics. However, the promise of these techniques supplements the maintenance concepts discussed.

Recent Senate hearings[4] projected over 1.7 million U.S. Army aircraft flying hours in FY 78. Therefore, any significant savings in cost per flight hour has a sizeable annual savings impact in the operating and maintenance portion of U.S. Army aircraft engine Life Cycle Costs. The same concept also applies to the U.S. Navy and Air Force who fly many more hours. One concludes, therefore, that the military Life Cycle Cost savings potential is tremendous.

LIFE-CYCLE ANALYSIS
OF
AIRCRAFT TURBINE ENGINES

J. R. NELSON

The Rand Corporation
Santa Monica, California

LIFE-CYCLE ANALYSIS OF AIRCRAFT TURBINE ENGINES

J. R. Nelson

INTRODUCTION

This study concerns the *life-cycle analysis of aircraft turbine* engines. The term life-cycle analysis is used because benefits as well as costs are addressed for this very important aircraft subsystem. The overall study of aircraft turbine engines was initiated under the R&D and Acquisition Program at Rand, and early work included development of a technique for assessing the state-of-the-art of aircraft turbine engines in terms of performance characteristics sought at a key milestone date and then relating that state-of-the-art trend to acquisition costs (development and procurement). The present work was performed under the Logistics Program in FY 1977 where aspects of both acquisition and ownership were addressed. Ownership considerations were added to the acquisition work to provide a total life-cycle perspective.

Previous aircraft turbine engine work has been published in a number of Rand reports going back over a decade.* The latest engine work is summarized in R-2103/1-AF, *Life-Cycle Analysis of Aircraft Turbine Engines: Executive Summary*.

This presentation explands on that effort to include aircraft weapon system level considerations.

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*Watts, F. A., *Aircraft Turbine Engines: Development and Procurement Cost,* The Rand Corporation, RM-4670-PR (Abridged), November 1965; Large, J. P., *Estimating Aircraft Turbine Engine Costs*, The Rand Corporation, RM-6384/1-PR, September 1970; Pinkel, B. and J. R. Nelson, *A Critique of Turbine Engine Development Policy,* The Rand Corporation, RM-6100/1-PR, April 1970; Alexander, A. J., and J. R. Nelson, *Measuring Technological Change: Aircraft Turbine Engines,* The Rand Corporation, R-1017-ARPA/PR, April 1972; Shishko, R., *Technological Change Through Product Improvement in Aircraft Turbine Engines*, The Rand Corporation, R-1061-PR, May 1973; Nelson, J. R. and F. S. Timson, *Relating Technology to Acquisition Costs: Aircraft Turbine Engines,* The Rand Corporation, R-1288-PR, March 1974; and Nelson, J. R., *Performance/Schedule/Cost Tradeoffs and Risk Analysis for the Acquisition of Aircraft Turbine Engines: Applications of R-1288-PR Methodology,* The Rand Corporation, R-1781-PR, June 1975.

Approach to the Study

The study focuses on the needs of the planner (and the engine designer as well) early in the consideration of a new weapon system and the difficulty the planner has in attempting to reconcile, from a life-cycle perspective, the conflicting demands of high performance, constrained schedule, and low costs while attempting to give appropriate weight to program risk in terms of exposure of the program to performance degradation, schedule slippage, and cost growth.

The problem is one of visibility for an early planner. Visibility refers to understanding the magnitude of the total life-cycle cost, the proportions of costs (how they are apportioned between various phases and cost elements of the program), and what the trends of performance and costs have been over time for previous engines of a similar application. Such information can then be utilized to project what the new engine might cost for the performance desired. An understanding of what the drivers or key variables are concerning cost changes is required so that the planner can do tradeoffs during the initial design within acquisition, within ownership, and between acquisition and ownership phases of the program.

The objective of the study is to develop a methodology for the life-cycle analysis of engines which can relate performance, schedule, and cost tradeoffs, with schedule or time being treated explicitly as well as performance and cost. For instance, a planner is confronted with a threat scenario. There is a requirement for an aircraft to exceed the capability of that threat. An engine with certain performance characteristics is required by a certain date in order to obtain that aircraft requirement. Is the planner asking for an engine within the evolutionary state-of-the-art trend of engine technology or is he asking for a product that is significantly "pushing" the state-of-the-art? If the engine is "pushing" the state-of-the-art, what are the risks not only to the engine, but also to the entire program since the engine is frequently the pacing development item? If the engine is "pushing" the state-of-the-art, then not only must the evolutionary technology inherent in the state-of-the-art trend be transferred successfully to the development program, but some additional increment of technology must also be accomplished within that same development program. There is an exposure to risk regarding engine performance shortfall, schedule slippage, and cost growth, and those in turn pose risks for the entire weapon system.

Engines are an important subsystem and were selected for this study for several reasons: 1) in a new weapons system, a new engine is considered to be the pacing development item; 2) the engine subsystem viewpoint would be valuable to parallel the viewpoint obtained in life-cycle analysis studies concerning the weapon system as a whole; 3) engines have shown important evolutionary improvements in the state-of-the-art over the years and thus effects of life-cycle costs due to technological advances might be captured in an analysis of engines; and 4) it would appear that sufficient data would be available in order to analyze acquisition and ownership phases for engines. Engine data in the acquisition area are available from the engine contractors for the past 25-30 years. The data available in ownership must come from the military services and here the data is available only for the very recent past, in some cases, as little as one year.

The procedure in this study has been to: 1) collect and analyze detailed data for the various phases of the life cycle; 2) investigate cost estimating relationships (CERs) not only to obtain high statistical quality, but, of primary importance, to insure that the theoretical relationships are correct and in line with experience obtained in the field (thus increasing confidence in the validity of the models derived); and 3) apply the CERs to examples of interest (an application will be presented in this briefing showing the trend of life-cycle cost for fighter engines over the past several decades). Commercial experience has also been considered to determine if such experience might be relevant to the military environment.

The problem that has faced analysts in attempting to bring together all the elements of life-cycle cost has been the lack of detailed, well-defined data covering a significant period of time. This is true in particular in the ownership area with regard to engine costs at the depot and at the base. This study has benefited from extensive data collection efforts in support of past engine studies over the years as well as additional data collection efforts conducted as part of this study. The RDT&E and procurement data have been obtained from the engine contractors and, for the most part, are well defined and disaggregated to the particular cost elements of concern for significant periods of time, in some cases covering 25-30 years. This provides a relatively good data base for use in developing models of the R&D phase. The problem that has confronted analysts (and still does today) in the ownership area is that the military services maintain data

for only a limited period of time at the base and depot. One to two years of data have been obtained for some cost elements and thus the data are highly cross-sectional in nature. Thus, the ownership models should be viewed with caution. Improvements in the ownership models should be possible through continued collection of data.

The approach in this study has been to utilize a measure of the state-of-the-art to represent changes in technology that have affected engine life-cycle cost. Thus, this technique provides a significant change (and it is hoped a considerable improvement) from past studies which have not utilized such an approach. A further intent is to quantify effects on cost due to selection and change of development and production schedule, as well as performance requirements. This measure aids in providing an integrated approach to the engine life-cycle analysis in terms of relating the benefits to be accrued from the state-of-the-art improvements to the schedules and costs for obtaining such improvements. The methodology can then bring together magnitudes, distributions, and trends of costs to provide the helpful insights required by the planner.

Data Analysis Results from this Study

Previous studies have indicated that the ownership cost of engines is the smaller part of the total life-cycle cost; that the major cost is in development and procurement. (Fuel and attrition are not considered in this analysis.) These previous studies have suffered from significant data problems. Not only are there problems of missing data, but also misinterpreted and misused data.* There is today an increasing awareness on the part of the military services that ownership costs are larger than previously indicated. Indeed, this study yields results just opposite to those of previous studies: ownership cost is the larger part of the total life-cycle cost of an engine.

*Some problems include: cost elements not clearly defined, elements that change definition over time, labor rates that are not fully burdened, use of steady-state cost of a current system to project average cost to a new system (instead of averaging over time), and major cost elements omitted.

If the component improvement program (the continuing improvement of the engine beyond its development) and the spare engines necessary to support the installed inventory are included in the definition of ownership cost, then the findings indicate that, for a 15-year operational span, ownership is about two-thirds of the total cost for the engine; ownership is <u>twice</u> acquisition cost. This is true for current supersonic fighter engines as well as subsonic transport and bomber engines.* After achieving operational status, the continuing development costs (Component Improvement Program--CIP) during the course of 15 years of operation are at least as large as development cost to Model Qualification Test. A problem with the CIP money has been the inability to separate out the costs attributable directly to specific functional areas for which the money was spent, namely performance, additional applications of the engine, improvement in reliability, correction of service-revealed deficiences, reduction of cost, and development of base and depot repair procedures. The CIP costs must be disaggregated if cost is to be linked to obtaining a specific improvement, for instance, reliability.

A major finding of this study differing from previous published results is that the cost of repair of engines in the depot (including overhaul, modifications, minor repairs that the base does not have the capability to perform, backshop support of the base as well as the overhaul line, the replacement of condemned reparable parts and the full cost of expendable parts) can be as large over a 15-year life cycle as the procurement price of the engine. A single overhaul at a depot costs on the order of 10 to 20 percent of an engine's current price. Repair and replacement of reparable parts not only for the overhaul line, but also for those components that come in from a base, are repaired and go back to the base, and the replacement of those parts that are condemned can add anywhere from 10 to 100 percent additional cost to the overhaul cost, depending on what might be hapenning to a particular engine in a given year and also what might be happening within the budgetary cycle for a particular year. These costs can fluctuate widely from year to year due to these factors. This is why the availability of a longitudinal data base is so important.

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*All costs are expressed in constant dollars--discounting may change some findings, depending on the distribution of costs over the time horizon of interest and the discount rate assumed.

When it is also considered that an engine is overhauled three to six times in its lifetime depending upon the application (subsonic engines at the lower end and supersonic engines at the upper end of the range), we find that depot repair cost alone can be as large as procurement cost.

The base cost is significant; it is smaller than the depot cost, but still of a considerable magnitude, depending again upon the particular application. At the base, it is necessary to count the people active in the engine shop rather than to look at any particular data system that reports the work actually accomplished, because costs reflect the people available in the shop, not only the work load actually accomplished. In addition, the cost responsibility center data (from the Resource Management System) are necessary to obtain costs for supply support.

Commercial experience has been investigated to find lessons that might be applicable to the military. Results indicate that commercial ownership costs are apparently lower than military costs due to the airlines having a different operating environment (peacetime steady-state—although their economic enviroment may not be characterized as steady state) and different policies concerning operations (higher utilization, power management) and maintenance (modular design, on-condition maintenance) of their engines.*

AIRCRAFT TURBINE ENGINE LIFE-CYCLE ANALYSIS METHODOLOGY

The technique employed for assessing the state-of-the-art of aircraft turbine engines relates the time of arrival of the 150-hour Model Qualification Test to a bundle of engine performance characteristics desired in the engine. The data are for 26 engine programs, covering 30 years of history from 1942 to 1972. The 150-hour Model Qualification Test date is the key military milestone date at which time the engine is considered suitable for operational use. Thus, a relationship is obtained for the performance characteristics sought by the user over time, thereby obtaining a proxy for the measurement of the state-of-the-art with time. In this study, not only the time of arrival, but also a delta time of arrival (the

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*More detailed information is contained in Nelson, J. R., *Life-Cycle Analysis of Aircraft Turbine Engines: Executive Summary*, The Rand Corporation, R-2103/1-AF, March 1977.

characteristics sought at a certain date compared to when those characteristics were expected to arrive) are both employed in the cost models in order to ascertain the cost effect of not only the trend of the state-of-the art, but also whether a particular engine is "pushing" the state-of-the art within the trend of time and how that might affect cost.

Chart 1 presents the models obtained to date.* The state-of-the-art trend (time of arrival) is shown with important characteristics sought in an engine; temperature, weight, pressure, specific fuel consumption, and thrust. Below each of the variables is the sign of the coefficient as it enters the model. In addition to all of the models having statistical significance, the variables entering the models are perceived to be behaving correctly with regard to theoretical relationships; they corroborate the experience of the designers and users in that the direction of the variables are correct, giving confidence to the validity of the model. This is true for all the models presented. For instance, in the state-of-the-art trend, where it is expected that technology will be improving with time, turbine inlet temperature is a highly desirable characteristic in an engine; it is constantly increased, it does indeed improve with time, and we do have a positive coefficient for how it enters the TOA relationship. The same with the pressure term; it is expected to increase with time. Variables that would be expected to be reduced with time, such as weight and specific fuel consumption, are entering with negative coefficients. Thrust is positive; the average thrust size of engines have been growing with time.

We make use of TOA and ΔTOA in the cost models. For instance, we've obtained a model for development cost. Here, the cost of the engine to be developed to the 150-hour test is a function of development time period (how long the engine was under development), the physical size of the engine, the Δ time of arrival (how the engine was pushing the state-of-the-art), and the complexity of the engine (Mach number measuring the flight environment). All of these variables enter positively, all having the effect of increasing the development cost of the engine. We see similar results in looking at production costs and we show several ways of achieving development and production costs, thus obtaining a method for trading off the acquisition performance/schedule/cost for an engine.

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*Additional details, together with the coefficients, are shown in Nelson, J. R., *Life-Cycle Analysis of Aircraft Turbine Engines: Executive Summary*, The Rand Corporation, R-2103/1-PR, March 1977.

The new work is shown at the bottom of the chart: models for depot and base costs. These two areas are principal cost elements with regard to the ownership of engines (in additional, whole spare engines and CIP are also considered part of ownership). Note that these two models each utilize a different definition of the engine flying hour, the utilization measure that was used for engine life-cycle costs. Costs incurred at the air base depend on "consumed" flying hours, the flying hours that the operator consumes in the field. There is also the flying hour "restored" by the depot; that is, the depot repairs engines and restores flying time to the engines and returns them to the user. In a steady-state situation of supply equal to demand, what the user is demanding by his consumption in the field, the depot is supplying by restoring these engines to flying status. Thus, in a steady-state situation, consumed and restored flying hours would be approximately the same. A problem arises in the analysis because the life cycle is not entirely steady state. Furthermore, we have only limited cross-sectional data at the depot (for a year or two) and in any given year the consumed and restored flying hours can be very different. For instance, in the initial phase of a program when new engines are being introduced, the fleet is flying at a higher rate, yet not many engines are showing up at the depot. Thus, consumed flying hours are much higher than restored hours. Also, across the total program, consumed hours would exceed restored hours because when an engine is finally condemned and disposed of, it has some flying hours on it (it is not sent back to the depot to be restored to zero time before being thrown away). Thus, more hours are consumed than restored during the engine life cycle. In any particular year, however, more engine hours may be restored in the depot than consumed in the field (for example, a major modification program may cause engines to be sent to the depot for repairs even though they have accumulated relatively few hours). Thus, these two measures are important to understand and keep separate; in the depot, the restored flying hour is the preferred unit for tracking depot costs, and at the base, the consumed flying hour is the preferred unit for tracking base costs.

The key independent variables for depot and base costs are time between overhaul and current unit selling price of the engine. At the depot, the average time between overhaul (ATBO) is of interest; when an engine actually comes in to be fixed. At a base, the maximum time between overhaul (MTBO) is of concern since it is the policy that sets how long an engine can stay

in the field before it is mandatory for it to be returned to the depot for overhaul. The reason this is of interest at the base is because the base keys its scheduled periodic inspection, which is a major part of the propulsion shop workload, to the MTBO. It is also interesting to note that the engine unit selling price indirectly brings into the cost relationships the state-of-the-art in terms of TOA and ΔTOA, because they were utilized in determining the production unit price. Thus, the time of arrival technique is indirectly represented in the depot and base cost estimation models.

How might a planner make use of this technique in attempting to understand the subsystem tradeoffs confronting him during the design of a new weapon system? Let's look at a particular example.

SUBSYSTEM LEVEL CONSIDERATIONS

This example is presented to demonstrate the application of the engine life-cycle analysis technique at the subsystem level. The engines to be compared are shown in Chart 2. They represent fighter aircraft engines of the 1950s and 1970s, and a projected fighter aircraft engine for the 1980s, to assess the trend in performance and cost. The J75 of the 1950s is a trend engine (the time-of-arrival technique provides a point very close to the 45 deg line). A "J75/F100" of the 1970s is also shown. This hypothetical engine is of J75 size (24,000 lbs thrust), but is an afterburning turbofan of the F100 type. Its characteristics are purposely selected to result in a trend engine to compare directly to the J75. The actual F100 data is deleted due to security classification, but the analysis results for this engine are also presented. Also shown in the chart (separated by the line) is a hypothetical advanced turbofan (ATF) that might be employed in the 1980s. What can the application of this technique tell us about these engines?

All of the engines on this chart have a thrust rating of approximately 24,000 lbs. It can be seen that in going from the J75 of the 1950s to the J75-sized F100 type of the 1970s, that a significant improvement is obtained in reduction of engine weight and in lower specific fuel consumption. (Not shown, but equally important in terms of aircraft system effects is the smaller physical size of the latter engine in terms of frontal area and volume.) Note the significant increase in temperature and pressure levels for the newer engine shown.

In subsequent charts, two versions of the newer J75/F100 engine will be shown, a Mach 2 version to compare directly to the J75 at Mach 2, and also a Mach 2.5 version which can then be compared directly to the actual F100. Future charts will also involve the ATF engine at two different weights in order to present a comparison of a trend engine and an advanced engine for the 1980s.

Chart 3 presents the plot of the engine data base using the time-of-arrival technique as explained in several previous Rand publications. The notion is that engines follow an evolutionary trend, and that a particular engine's time-of-arrival is calculated on the basis of a bundle of performance characteristics sought at a particular date.* An engine showing up when expected is considered a trend engine, whereas an engine falling significantly above the 45 deg line (its bundle of characteristics indicate that it would be expected to show up at a certain date but it actually shows up earlier) is considered an advanced engine. In the figure are the J75; a trend engine of the 1950s; the J75/F100, a hypothetical trend engine of the 1970s; the actual F100, an advanced engine of the 1970s; and the two versions of the ATF for the 1980s, on trend and advanced.

Chart 4 presents a hypothetical baseline program to calculate life-cycle costs for the various engine versions on a common basis. Costs are in constant 1975 dollars; no discounting has been employed in this example, nor are any costs allocated for fuel or attrition.

Chart 5 presents a bar chart comparison of the engines described on Chart 2. The actual J75 of the 1950s (on trend at Mach 2) is calculated to have cost approximately $4 billion in total life-cycle cost (1975 dollars). The increasing cost due to the improvement in the state-of-the-art to obtain the hypothetical J75/F100 in the 1970s on trend at Mach 2 is also shown, as is the increase to obtain a Mach 2.5 version and finally, the actual F100 which is an advanced engine of the 1970s at Mach 2.5. Of particular interest is that the depot cost is growing not only in terms of magnitude of dollars, but also as an increasing percentage of the total. These costs are for the engine only, at the subsystem level, and not related in any way to the impact that this engine has on total weapon system performance and cost. It may

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*For further discussion, see Alexander, A. J., and J. R. Nelson, *Measuring Technological Change: Aircraft Turbine Engines*, The Rand Corporation, R-1017-ARPA/PR, April 1972; and Nelson, J. R. and F. S. Timson, *Relating Technology to Acquisition Costs: Aircraft Turbine Engines*, The Rand Corporation, R-1288-PR, March 1974.

very well be that the F100 is well worth the cost when related to what it does to improve mission capability, reduce fuel consumption, and reduce the physical size (and thus fuel cost and airframe development and procurement cost) of the F-15 aircraft for its mission requirement. Thus, in attempting to achieve the F-15 mission requirement, the advanced engine design may have been the most "cost-effective" solution at the system level.

What would the technique indicate concerning derating the F100 engine? Commercial experience presents the only available data concerning the effect that derating an engine's performance has on the life extension of engine parts. Commercial data indicates that by reducing thrust approximately ten percent for the first and second generation commercial engines (the JT3D and the JT8D), approximately a 50 percent increase in the life of hot parts (combustor and turbine was achieved). If the same percentage improvement in ATBO/MTBO could be achieved by similarly derating the F100, then the life-cycle cost estimating model would indicate a life-cycle cost savings of approximately $1 billion.

One difficulty in using these models is that they cannot determine what investment is required to obtain these improvements. They only tell what the savings are if the improvements are indeed realized. These cost savings are, as indicated in Chart 6, primarily coming from the reduction in the depot costs as shown by the proportions of the bar chart. It must be realized also that there may not be a one-to-one relationship between military and commercial experience. Military use may require considerably more cycling of an engine which also causes reliability problems, thus military engines may not achieve the same cost improvement as commercial experience would indicate for a given degree of derating.

It must also be noted that the models are based on data from past programs and thus they reflect the ways things were done in the past. That is, the projected costs for the F100 reflect costs which would be associated with it if it were being treated in operations and maintenance in a manner similar to the J75. However, there are expected to be changes in the F100 ownership process; it is of modular design and will follow an on-condition maintenance policy. These features are expected to reduce ownership cost. Thus, the numbers presented on the chart may reflect a pessimistically high cost, i.e., as if these F100 features don't provide any cost reduction. If, however, these new concepts could in some way result in obtaining an improved ATBO/MTBO, then the model could be used to predict the associated cost reduction.

One of the preceding calculations estimated the reduction in life-cycle cost that might be achieved through improvement in ATBO/MTBO, which in turn could be obtained by derating the engine. The models could also be employed in attempting to address another question; what reductions in life-cycle cost might be achieved through technology improvements? For instance, shown in Chart 7 are the ATF options defined earlier; an advanced engine for the 1980s with a baseline ATBO/MTBO (750/1200 hours), that same advanced engine with a 50 percent higher ATBO/MTBO, a trend engine at baseline ATBO/MTBO, and the same trend engine with a 50 percent higher ATBO/MTBO. The total life-cycle cost of each option is different as shown on the chart. These different costs could be obtained in different ways. For instance, obtaining an engine on trend, rather than advanced, might show a total life-cycle cost reduction of nearly $1 billion as indicated by comparing the two advanced bars with their comparable trend bars. On the other hand, if improvements could be made to reliability and durability (and thus in ATBO/MTBO) for a given kind of engine whether advanced or on trend, then the models would predict life-cycle cost savings on the order of $1.5 billion. Thus, the methodology can provide some indication of what the cost saving might be, given that a particular improvement is obtained, although it cannot predict how much it will cost to obtain a particular improvement, whether or not that improvement is obtainable, or how best to obtain it. Those kinds of decisions and considerations must be accomplished outside of this methodology and are in the province of interactions between the Air Force planners and technologists, and the engine and airframe manufacturers.

FINDINGS AT THE SUBSYSTEM LEVEL

Our study at the subsystem level has shown that it is possible to develop techniques in which life-cycle cost estimates can be made sensitive to performance and schedule so that cost magnitudes, proportions and trends, key cost drivers, and tradeoffs may be visible to a weapon system planner early in the concept formulation process, providing him useful insights. However, not all the tradeoffs that we would like to make are currently available. It is recommended that additional analytical work and data collection be continued to improve some of these models.

Our findings indicate that improvements in engine performance alone will increase engine life-cycle costs, and obtaining that engine performance earlier will further increase engine life-cycle cost. The depot appears to be an area where opportunity for significant cost savings exists. For instance, we estimate that a 50 percent improvement in ATBO/MTBO for the F100 engine would yield about a billion dollar reduction in engine life-cycle cost.

In the final analysis, the engine design choices must be made on the basis of how the engine affects the performance and cost of the entire weapon system. The remainder of this presentation is devoted to an exploration of how our engine cost estimation methodology might be utilized in system-level design decisions.

SYSTEM LEVEL CONSIDERATIONS

The main objective of applying this analysis methodology at the system level is to explore how engine technology improvement effects might interact with specific mission requirements and system/subsystem specifications. In addressing this area, it was necessary to seek assistance from airframe manufacturers to obtain the necessary understanding of how system/subsystem interactions will depend on a specific mission requirement. McDonnell-Douglas provided assistance in examining an air superiority mission requirement, and Northrop provided assistance in examining an advanced tactical fighter requirement for the 1980s, part of their Advanced Technology Study (ATS). The Rand engine life cycle and Rand airframe RDT&E and procurement models were then utilized, together with the airframe information concerning system design and fuel consumption for the particular mission requirement, to determine the cost comparisons that are presented.

Certainly, "optimum" answers were not obtainable for the time and effort involved in this illustrative analysis, but the assistance of the two airframe companies was instrumental in illuminating system-level tradeoff considerations, which in turn improves the perception of the usefulness of the subsystem results.

The particular missions looked at were the F15 air superiority mission (in which we received McDonnell-Douglas' assistance) and the ATS mission (in which we received Northrop's assistance). In the air superiority case, a range of engine thrust/weight ratio was investigated for a parametric family of trend engines of the 1960s, 1970s, and 1980s. The thermodynamic engine cycle of the F100 was used throughout the analysis. A fixed procurement of

aircraft, constant airframe technology, and twin-engine configurations were additional ground rules, again for analytical simplicity. For the ATS mission requirement, we looked at both thrust/weight and thermodynamic cycle variations for two specific design points for an F100-type engine. Again, additional ground rules included fixed force size, constant airframe technology, and twin-engine configuration. These restrictions concerning airframe technology and configuration (and engine thermodynamic cycles in the case of McDonnell-Douglas) were necessary because of the limited scope of this illustrative analysis. In order to do a total optimization study for each particular mission requirement, variation of engine thrust/weight, engine thermodynamic cycle, and aircraft configuration would have resulted in a very large study effort which neither McDonnell-Douglas nor Northrop could undertake in this situation. However, just such an extensive study would normally be accomplished during concept formulation for a new weapon system.

Chart 8 presents the results of the variation in aircraft takeoff gross weight with changes in engine thrust/weight ratio for the McDonnell-Douglas air superiority mission. The improvement obtained in reducing aircraft takeoff gross weight as thrust/weight ratio is increased from four to eight is particularly evident. The point near the engine thrust/weight of eight represents the design point for the F-15. The engine thrust/weight of four is an engine of about 45,000 lbs thrust. Thus, a considerably smaller engine thrust size results as engine thrust/weight increases because the aircraft weight and fuel consumption are reduced, resulting in a significantly lower aircraft gross weight. It should be noted further that improvements in thrust/weight ratio from eight to 12 provide much less reduction in airframe takeoff gross weight for <u>this particular air superiority mission.</u>

Chart 9 presents design points from the Northop Advanced Technology study mission. It can be seen that improvements in thrust/weight ratio and in cycle thermodynamics (from a baseline F100 engine) do result in a significant reduction in aircraft takeoff gross weight for this particular mission requirement. The main point of this chart is that the effect of engine technology with regard to thrust/weight and thermodynamic cycle is extremely sensitive to the mission requirement being addressed.

A hypothetical baseline program similar to the engine example is shown in Chart 10. In this case, the fuel and airframe development and procurement costs are also addressed. For the F15 air superiority mission, the F100 engine consumes 1250 gallons of fuel per flight hour, at 44¢ per gallon, with fuel consumption at other engine thrust/weight design points scaled to the thrust of the engine. Thus, for the thrust/weight ratio of four, with an aircraft takeoff gross weight in excess of 70,000 lbs, the engine size was approximately double the F100 size, and thus fuel consumption was scaled to that thrust. In the case of the Northrop design, the F100 consumed 1100 gallons of fuel per flying hour, at 44¢ per gallon, and a ten percent SFC improvement was credited to the new advanced turbofan (ATF) engine for the Advanced Technology Study (ATS) fighter. Airframe costs were estimated using the Rand DAPCA model, in 1975 dollars. The number of airframes procured is consistent with the number of engines being procured. RDT&E and procurement costs assume fixed airframe technology and no airframe operating and support costs were estimated. It is important to understand that the airframe technology remained constant in each case (but was different for each case) and only the thrust/weight ratio varied in the case of the F15 air superiority mission, and the engine thrust/weight and fuel consumption varied in the case of the ATS mission.

The cost results for the air superiority mission at selected engine thrust/weight values are presented in Chart 11. The chart indicates that for a fixed air superiority mission requirement, increasing engine thrust/weight from four to eight, even though more technology is required, results in lower total system costs. Total cost comprises the engine life-cycle cost, airframe RDT&E and procurement cost, and fuel cost. The cost is lower when using the more advanced engine because the physical size and weight of the engine are reduced, resulting in a smaller airframe to achieve the same mission. Going from thrust/weight of eight to thrust/weight of 12 results in little additional cost reduction because the airframe does not reduce in size as much and because the specific fuel consumption was the same (only thrust/weight for the engine was being varied). Chart 12 shows a second set of bar charts in which a 50 percent improvement in ATBO/MTBO is presented. Again, notable savings for the engine are achieved, particularly because of cost reduction at the depot. Thus, in <u>this particular air superiority mission</u>, it would appear that use of future technology advances to cause a 50 percent increase in ATBO/MTBO would produce more cost reduction than if the same technology investment were used to reduce thrust/weight ratio from eight to 12.

When the mission requirement is changed, the cost implications change. As shown in Chart 13, there is a cost reduction in terms of the sum of total life-cycle cost for engine, airframe RDT&E and procurement, and fuel consumption in going from an F100 design to an advanced turbofan engine. The ATS mission requirement stresses different aspects of performance for the engine. For the technology represented by the advanced engine design, the result is a smaller and more efficient engine and hence smaller airframe size for that improved technology over what was obtainable from the F100 in this mission. Thus again, it is the mission requirement which highlights the benefit of specific technology improvements and their impact on cost reduction. Chart 14 presents a second set of bars, again showing that a 50 percent improvement in ATBO/MTBO will indeed provide a significant saving in engine life-cycle cost. This saving is about in line with the saving achieved by going to higher performance; a different outcome from the air superiority findings because the mission requirement is different.

SUMMARY

Thus, in summary, it is the mission requirement which will determine what the potential benefits will be for particular improvements achieved in technology programs. There is an interaction of decisionmaking in formulating new weapon system concepts and in determining the engine contribution to a new system; what is the mission requirement, what are the system level tradeoffs, and finally, down to what are the subsystem level tradeoffs.

A finding of this analysis is that substantial reductions in total life-cycle cost can be achieved by improving engine durability/reliability or by improving engine performance. Thus, a balanced approach toward the funding of engine technology programs seems warranted, with some support for durability/reliability improvements as well as performance improvements. In part, this is because there are diminishing impacts on continued performance gains provided by additional technology. For tactical fighters, there was significant gain in going from a thrust/weight ratio of four to eight; there appears to be less significant gains in going from eight to 12, but this is highly dependent upon the particular mission requirement.

"Paper" gains must be distinguished from "real" gains. When engine technology improvements result in a reduction of airframe weight and a reduction of fuel consumption, "real" cost reductions are to be expected in the new system. The airframe development and procurement cost will be less for a smaller airframe, and the decreased fuel utilized during the life of that weapon system will yield additional savings. In assessing the expected gains from an improvement in durability/reliability as represented by the ATBO/MTBO analysis, part of that cost reduction may be "paper" in the sense that it may not be fully reflected in the O&S budget for that system. Labor reduction at the base and at the depot may be achieved for a particular program, but may be reallocated to other programs and therefore not disappear from the Air Force budget. Thus, the Air Force budget may not be reduced to the extent indicated by the apparent cost reduction in the program.

It should also be remembered that some technology programs are "neutral" in character when attempting to assess whether they would benefit performance or reliability. For instance, a new turbine material providing higher temperature/stress capability can benefit performance if utilized to gain higher operating temperatures while retaining the same stress level of the previous material. This same material temperature/stress improvement could also be utilized by operating at the previous temperature level, but at some lower stress level, thus providing additional durability in that particular part. Thus, care must be used in separating technology programs with regard to whether they are performance oriented, durability oriented, or neutral in character.

Chart 1

MILITARY LIFE-CYCLE ANALYSIS MODELS

- State-of-Art Trend: f(TEMP, TOTPRS, WEIGHT, SFC, MAX THRUST)
- Development Cost ($M): f(DEVEL TIME, MAX THRUST, ΔTOA, MACH NO.)
- Component Improvement Cost ($M): f(MAX THRUST, ΔTOA, OPERTIME)
- Total Development Cost ($M): f(MACH NO., QTY, MAX THRUST, ΔTOA)
- 1000th Unit Cost ($M): f(MAX THRUST, TOA, MACH NO., ΔTOA)
- Cumulative Production Quantity Cost ($M): f(QTY, MAX THRUST, MFR, ΔTOA, MACH NO., TOA)
- Depot Maintenance Cost per Engine Flying Hour Removed ($/EFHR): f(AVG.TBO, UNIT COST, OPERTIME, ΔTOA)
- Base Maintenance Cost per Engine Flying Hour Consumed ($/EFHC): f(MAX.TBO, OPERTIME, UNIT COST)

Chart 2

ENGINE DATA

	J75 (1950's)	J75/F100 (1970's)	F100	ATF (1980's)
THRUST, LB	24,000	24,000	Deleted due to security classification	24,000
WEIGHT, LB	5,950	3,500		2,400, 2,000
SFC, LB/HR/LB	.80	.70		.60
MACH No.	2.0	2.0, 2.5		2.5
TURBINE INLET TEMP °R	2,060	2,900		3,460
TOTPR LB/FT^2	16,700	51,200		75,000

Chart 3

MILITARY TURBINE ENGINE TIME OF ARRIVAL

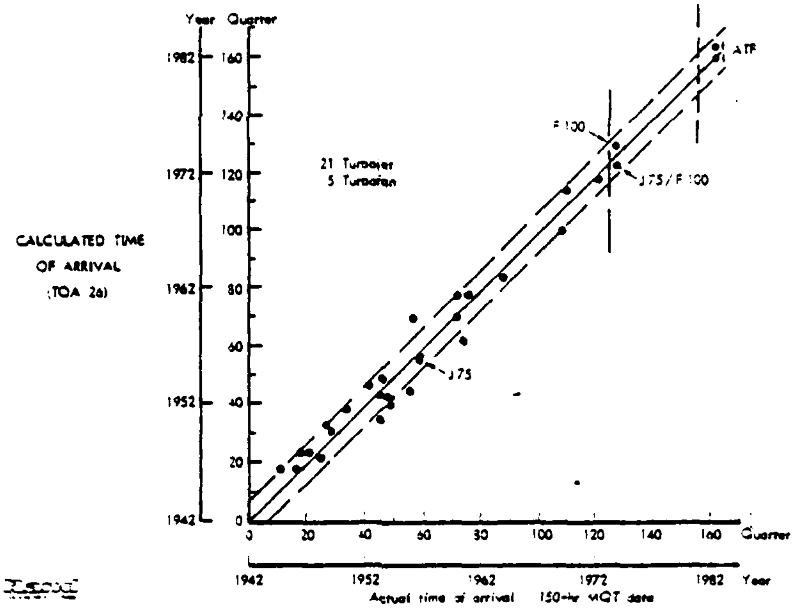

Chart 4

HYPOTHETICAL BASELINE PROGRAM

- 1975 DOLLARS
- 5 YEAR DEVELOPMENT
- 15 YEAR OPERATIONAL SPAN
- 6 MILLION ENGINE FLYING HOURS CONSUMED
- 5 MILLION ENGINE FLYING HOURS RESTORED
- 1935 ENGINES PROCURED
- 90% LEARNING (PRODUCTION)
- 750/1200 HRS MTBO/MTBO

NO FUEL OR ATTRITION INCLUDED

Chart 5

J75/F100 COMPARISON

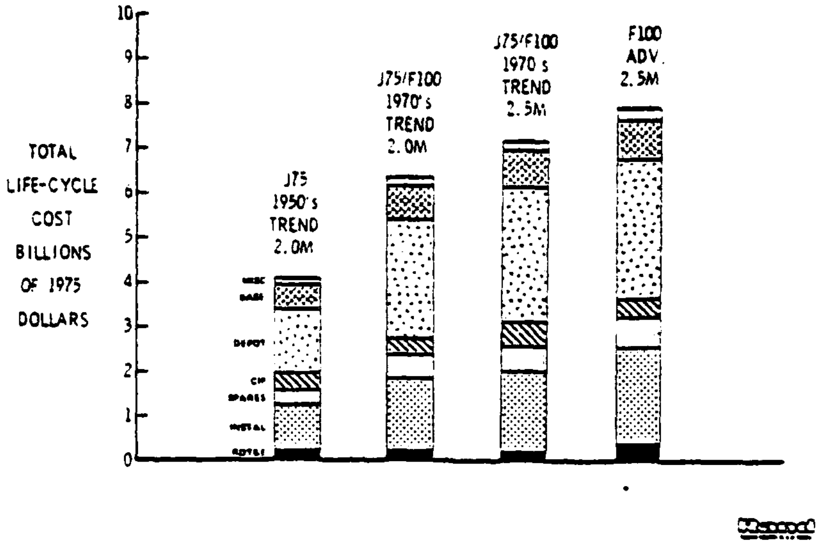

Chart 6

J75/F100 COMPARISON

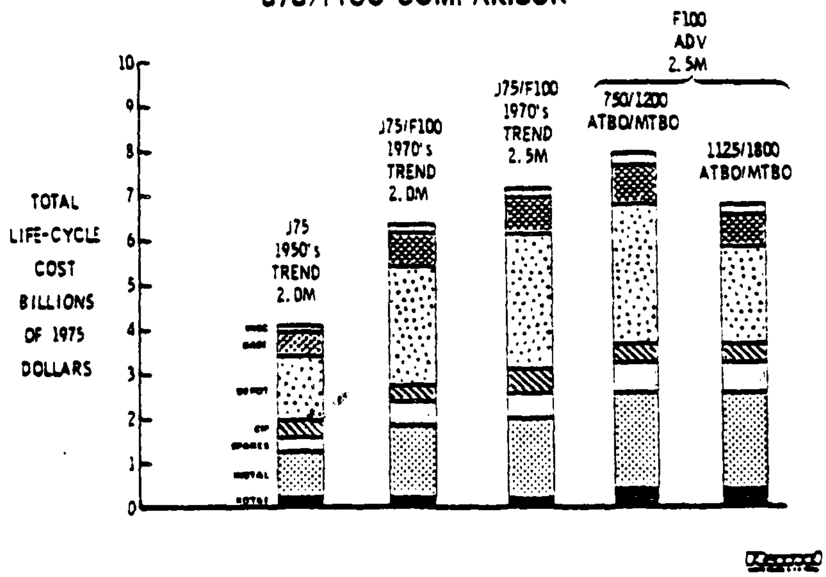

Chart 7

ATF OPTIONS

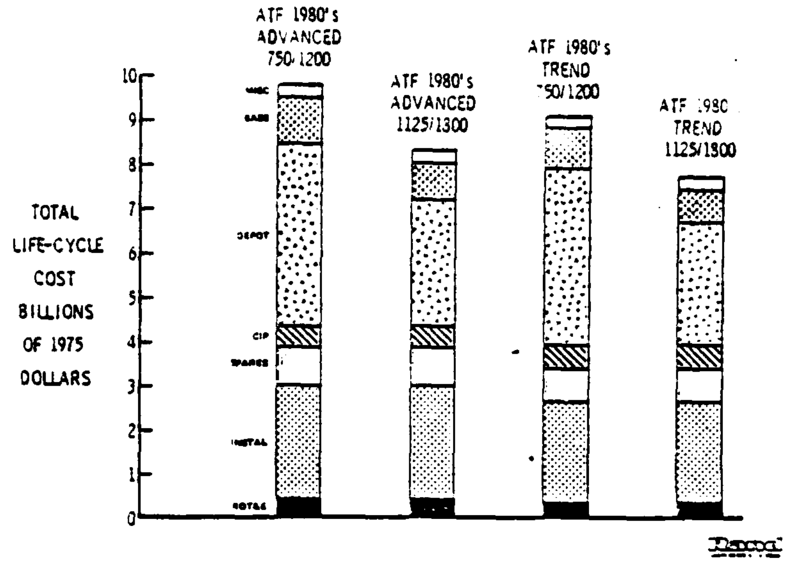

Chart 8

MISSION REQUIREMENT IMPACT ON AIRCRAFT TAKEOFF GROSS WEIGHT AND ENGINE THRUST WEIGHT TRADEOFF

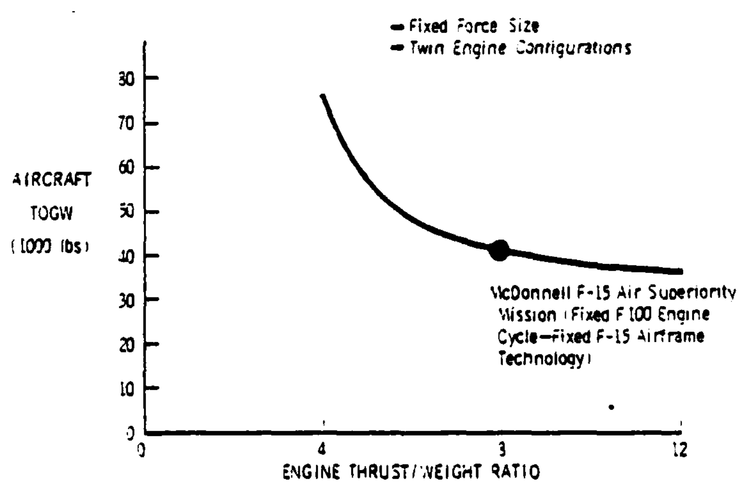

Chart 9

MISSION REQUIREMENT IMPACT ON AIRCRAFT TAKEOFF GROSS WEIGHT AND ENGINE THRUST/WEIGHT TRADEOFF AND ENGINE CYCLE

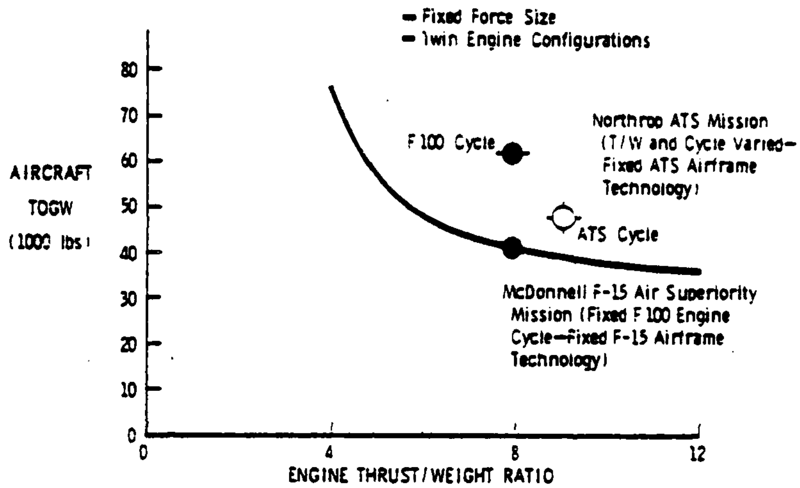

Chart 10

HYPOTHETICAL BASELINE PROGRAM

ENGINE

- 1975 DOLLARS
- 5 YEAR DEVELOPMENT
- 15 YEAR OPERATIONAL SPAN
- 6 MILLION ENGINE FLYING HOURS CONSUMED
- 5 MILLION ENGINE FLYING HOURS RESTORED
- 1935 ENGINES PROCURED
- 90% LEARNING (PRODUCTION)
- 750/1200 HRS ATBO/MTBO

FUEL

- F 15/F 100 – 1250 GAL/FH @ 44¢/GAL WITH FUEL CONSUMPTION SCALED TO THRUST
- ATF/F 100 – 1100 GAL/FH @ 44¢/GAL WITH 10% SFC IMPROVEMENT FOR ADVANCED ENGINE

AIRFRAME

- 1975 DOLLARS
- 729 AIRFRAMES PROCURED
- RDT&E AND PROCUREMENT ONLY
- FIXED AIRFRAME TECHNOLOGY

Chart 11

SYSTEM-LEVEL COST DIFFERENCES WITH ENGINE THRUST/WEIGHT VARIATIONS

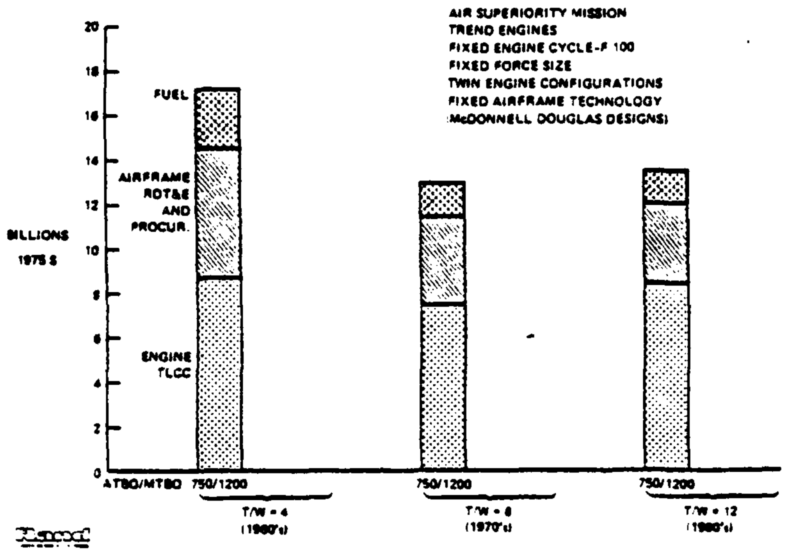

Chart 12

SYSTEM-LEVEL COST DIFFERENCES WITH ENGINE THRUST/WEIGHT VARIATIONS

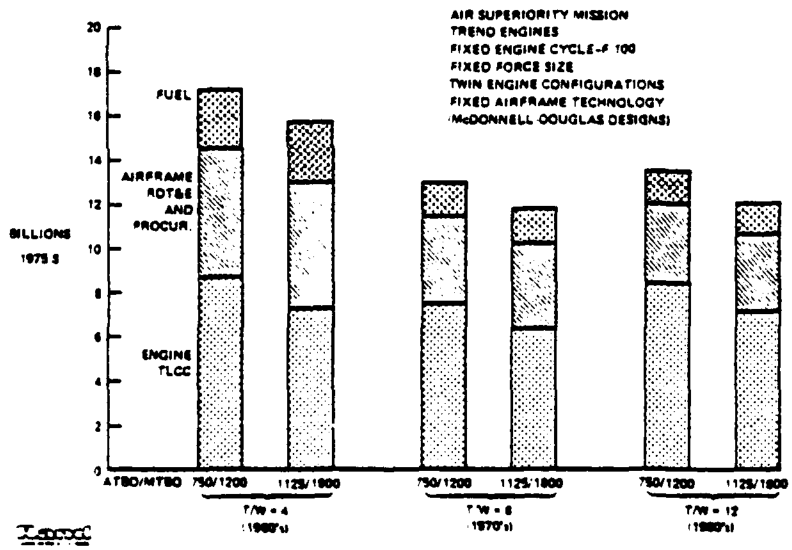

Chart 13

SYSTEM-LEVEL COST DIFFERENCES WITH ENGINE THRUST/WEIGHT AND CYCLE VARIATIONS

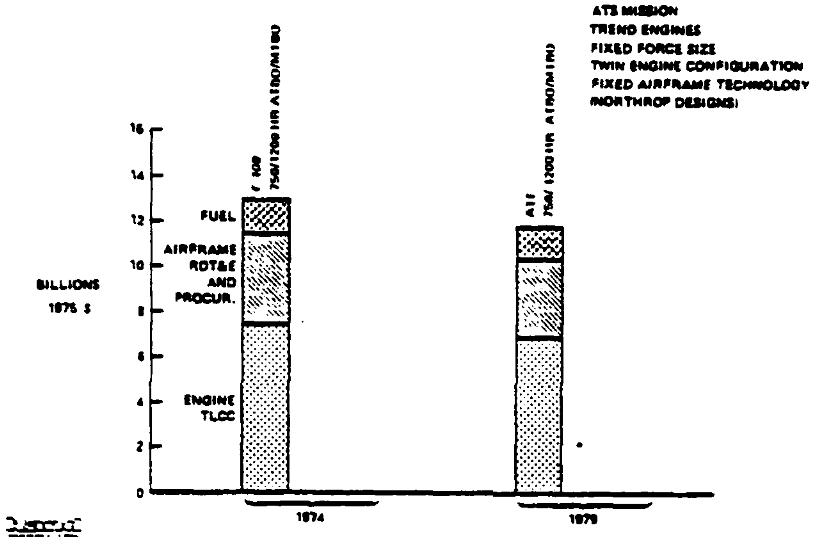

Chart 14

SYSTEM-LEVEL COST DIFFERENCES WITH ENGINE THRUST/WEIGHT AND CYCLE VARIATIONS

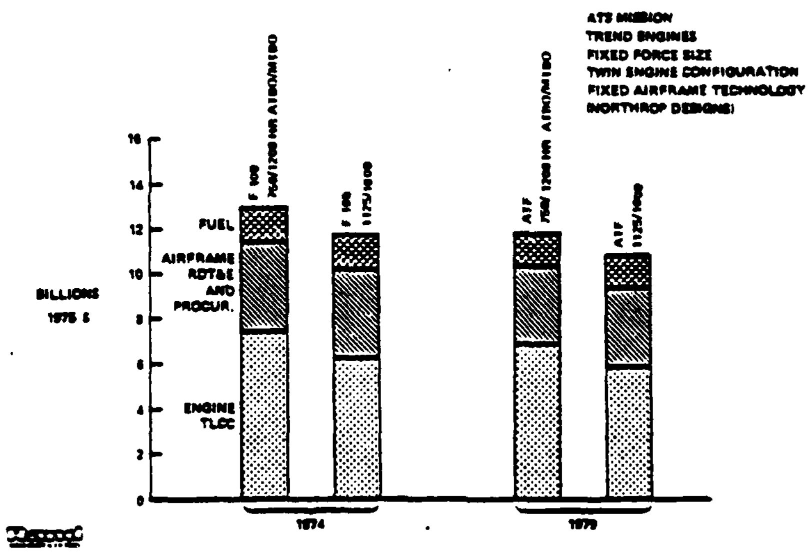

Table VI. Model 250-C20 Overhaul Time (Hours)

MODEL 250-C20
TIME-BETWEEN OVERHAUL

	COMPLETE ENGINE	MAJOR MODULE
COMPRESSOR	1500 HRS	3000 HRS
ACCESSORY GEARBOX	1500 HRS	ON-CONDITION
TURBINE	1500 HRS	3000 HRS WITH 1500 HR HOT SECTION MAINTENANCE

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ROLLS-ROYCE LIMITED
AERO DIVISION - BRISTOL

LOW COST DESIGN TECHNIQUES AND THEIR APPLICATION TO THE DESIGN OF THE ROLLS-ROYCE RB.401

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LOW COST DESIGN TECHNIQUES AND THEIR APPLICATION TO THE DESIGN OF THE ROLLS-ROYCE RB.401

1.0. INTRODUCTION

This paper describes:-

- The development and implementation of the procedure called Product Cost Control, used by Rolls-Royce to control costs.
- The consideration given during the design stage to factors affecting Life Cycle Costs.
- An analytical system to assess the Operational and Support elements of Life Cycle Costs.
- The low first cost and low cost of ownership features of the Rolls-Royce RB.401.

2.0. THE DEVELOPMENT AND IMPLEMENTATION OF PRODUCT COST CONTROL

2.1. Introduction of Value Engineering

Rolls-Royce, Bristol, has been addressing the problem of including cost as an engine design parameter since the middle 1960s when Value Engineering was introduced as a formal activity. The potential of the Value Engineering approach as a means of identifying ways of reducing the cost of components soon became apparent to those most closely involved. What was not fully recognised at the time was the difficulty, particularly in the cost reimbursement climate which then prevailed, of integrating a procedure, in which cost was the principal parameter, with existing procedures that only recognised levels of technical priority.

The Company Training College sponsored a Value Engineering course which over the years was attended by the majority of Designers, Detailers and Production Engineers and a Value Engineering Department was established within the Design Office. The department was staffed by Engineers with planning experience who, because of their location, became the main source of production engineering advice used by the Designer. However, their recommendations lacked commitment, for, unlike the Production Engineer they had no responsibility for the manufacturing programme. This factor, together with the problem of balancing cost and technical priorities, temporarily impeded progress toward achieving the full cost reduction potential of Value Engineering on defence projects.

2.2. Manufacturing Design Liaison

In the early 1970s a major re-organisation of the Manufacturing Department was initiated. Product Centres were established, each solely responsible for the supply, during the production programme, of a group of components. For example: Product Centre 2 is responsible for all the shafts of all projects; Product Centre 1 is responsible for all compressor blades; and so on. Each Centre is self-supporting in terms of Planning, Estimating, Purchasing, Sub-Contracting and Quality. The advantages of an organisation of this type include specialisation, improved capital plant planning and, significantly for the subject of this paper, positive identification during the design phase of the Manager, and the team, having supply responsibility for each component in the production

phase. The re-organisation opened the way to new opportunities by which production engineering advice could be made available to the Designer. A Manufacturing Design Liaison system was established replacing the Value Engineering Department. (See Fig. 1). Manufacturing Design Liaison Engineers were sited in the Design Office, assigned to projects with others sited in the Product Centres, assigned to component groups. The objective of the network was to ensure that Material Purchasing Specialists and Production Engineers who have subsequent responsibility for producing the parts are able, through joint discussion with the Designer, to make a contribution during the design stage. It was the Liaison Engineer's responsibility to recognise the right time for such discussion and identify the correct manufacturing representatives. An important part of his job was to make certain that Production Engineers put their case in quantitative terms and numerically evaluated the implications of alternative manufacturing approaches, so that Value Analysis could be carried out by the Designer.

2.3. RB.401 Design Management Style

The Liaison activity became effective during the preliminary design stage of the RB.401. The RB.401 design team had recognised from the start the importance to the commercial success of the project, of low initial cost and low cost of ownership. The Project Chief Designer adopted a Management style in which Production Engineering, Product Support and Business Planning were required to contribute in a quantitative way to design decision-making jointly with Performance, Stress and Weight Departments. (See Fig. 2). Production Engineering was represented by the appropriate Manufacturing Design Liaison Engineer who was, therefore, able to ensure effective Production contribution through the Liaison network.

At this stage the importance of considered cost targets became apparent. Identifying and publishing within the Design Office a list of the major component targets, together with the latest estimate and the name of the Designer responsible, soon promoted an aggressive approach. Placard displays, frequently updated, of the emerging cost breakdown gave visibility to the whole team of the results of their efforts. Not only did this foster the team approach and increase their resolve, it also enabled them to demonstrate a commitment to

cost. Equally, there are other targets, such as timescale, to be met and there is a very understandable tendency to continue a successful search for cost reduction when it would be more cost effective to issue the scheme and make the hardware.

Not surprisingly this co-ordinated effort was successful in reducing the engine cost. (See Fig. 3). Fundamental to this success was:-

- The direct, timely and committed involvement of Engineering, Production and Commercial line management.
- Determination to trade cost with other parameters.

2.4. Product Cost Control Procedure

If the participation of line management is considered to be essential, then formal working procedures are required which are integrated with, and not superimposed upon other working procedures. The procedure, identified under the title "Product Cost Control", which is based on our RB.401 experience, is applicable to new design schemes for all our new and existing projects. (See Fig. 4). It is fully integrated and compatible with other working procedures and practices.

Product Cost Control requires the Marketing Department to determine type, size, price and possible programme for a new engine. On the basis of the price and programme, it is Business Planning's responsibility, taking account of the investment required and other business considerations, to establish a manufacturing factory cost. The factory cost figure is passed to the Design Cost Control Group which is responsible for assigning target costs to component level. As the design starts, this Group has the responsibility of informing the Designer of the target cost for his scheme and arranging for appropriate Manufacturing advice to be given. As the scheme nears completion the Group request a formal estimate (for an example of the proforma see Fig. 5) from Manufacturing to indicate how the scheme relates to the target cost. In making the request, additional information affecting cost, such as surface finish, similarity to other existing components and production rate, not apparent on the scheme, is provided to assist the Production Estimator.

The Estimator can also make use of a comprehensive data-based information service so that data on similar components in manufacture

can be investigated, parameters available include:-

- Standard times
- Batch quantities
- Historic actual batch times
- Purchase on-order prices
- Planning index sheets

All readily available on Visual Display Units.

On completion, providing the target cost can be met, the estimate is returned to the Design Cost Control Group, ideally before scheme issue. The Group ensures that the manufacturing drawing includes features on which the estimate is based. At the manufacturing drawing issue stage the Production Engineer reviews the drawing and signs to indicate that no feature on the manufacturing drawing should prevent him meeting the target cost. During planning the Production Engineers chooses processes to meet the target cost level which he has previously accepted. When the instruction to manufacture reaches the shop floor a monitor of the method used and times achieved is maintained.

If at any of these stages it is recognised that the cost target cannot be reached then the necessary action is initiated through the feedback system. For example: if the Production Engineer realizes that he cannot meet the target at the scheme stage, he may be able to arrange for corrective design action through the Design Cost Control Group. If a design change is not possible, the Group, because it has an overall view of the emerging cost situation may recommend a re-allocation of cost from a component which is bettering the target. If re-allocation is not possible because the overall target is being exceeded, the Group consults with Business Planning, who may have some contingency or who may in turn consult Marketing. In this way Management is given visibility of emerging cost data at the earliest opportunity and the interdependence of departmental disciplines, helps to replace the hidden departmental contingencies with a realistic assessment of the risk.

2.5. The Design Cost Control Group

The Design Cost Control Group headed by a Designer of equal status

to the Project Chief Designers, is the hub of this activity. (See Fig. 6). The Group membership comprises representatives of Production Engineering, Business Planning and Procurement Departments, seconded to him but still on their parent department's payroll. The Production representatives are the previously mentioned Manufacturing Design Liaison Engineers but with revised job titles signifying the change to a line function.

3.0. LIFE CYCLE COST CONSIDERATIONS DURING PRELIMINARY DESIGN

Design decisions play a part in determining life cycle costs in a number of different ways. The degree of innovation, maintainability, secondary damage patterns, engine rating or sizing, component costs, are all contributing factors and their impact on engine life cycle costs can be evaluated during the design stage.

3.1. Technical Innovation

The most advantageous and cost effective approach to a new engine project is to ensure that proposed technical advances are demonstrated ahead of a committed programme. The technical background significantly contributes to the avoidance of cost escalation by minimising expensive modifications to development engines. If a new requirement can be met by a derivative of an existing engine then, compared with a new engine, the derivative engine offers the advantages of lower design and development costs, shorter time scales and less risk.

3.2. Maintainability Considerations

The basic maintainability characteristics of an engine are determined during the preliminary design, generally before a potential customer has decided his Operating and Support (O. & S.) policy. At this stage Rolls-Royce Product Support establish maintenance targets for the Designer, for access, inspection and servicing at all component and module levels. A Maintainability/Repairability Requirements Specification is issued to the Designer and a Product Support Engineer assigned to the Design Office so that the recommendations and requirements are recognised as the design takes shape. Built into modern engines are comprehensive health monitoring systems such as:-

- Borescope Facilities

- Vibration Transducer
- Oil System Monitoring Facilities
- Radio Isotope Inspection Facilities

all of which have a significant reducing influence on maintenance costs. To be effective these systems must be considered at an early design stage.

3.3. Secondary Damage

A Designer's consideration of secondary damage aspects is almost entirely based on the failure patterns experienced on earlier engines. Clearly having the minimum number of components which are as robust as possible is a sound principle. However, a major contribution can be made by an audit procedure by which the new designs are reviewed by Senior Engineers and Designers not directly associated with the project, thereby, ensuring that the lessons of yesterday's experience are built into tomorrow's engines.

3.4. Engine Rating

The rating of an engine has a significant influence on the life cycle cost performance of the engine and of the air frame system. Advanced combat aircraft are continually demanding more performance from the same powerplant volume. This can be achieved by dispensing with the conventional fixed stator outlet temperature or fixed fan speed limitations and permitting the engine to operate at constant non-dimensional rotational speed. This can be done within the aerodynamic constraints of the powerplant installation quite easily because there is no requirement for a larger air intake, but component life can be adversely affected, particularly if the engine is to operate at high flight speeds and thus at high levels of inlet temperature.

4.0. LIFE CYCLE COST ANALYSIS

If the Western World is to avoid spending a high proportion of Gross National Product on defence, each weapon system, training or transport unit must be economically superior to those of the opposing forces. This objective raises life cycle costs to a level of importance (long recognised by the airline industry) equal to performance in the overall assessment of a project and

this in turn necessitates an in depth understanding of costs during all phases of an engine's life cycle.

4.1. Life Cycle Cost Elements

The elements which contribute to the total life cycle cost of an engine are:-

- Research, Development, Testing and Evaluation (R.D.T. & E.)
- Installed Engines
- Initial Outfitting
- Operations and Support (O. & S.)

The costs of R.D.T. & E., Installed Engines and Initial Outfitting have been estimated and monitored over a number of years and the process of obtaining estimates is, therefore, clearly understood. The O. & S. phase of a military engine's life cycle is currently the sector which although the management systems are well understood, has lacked the mechanisms for detailed cost evaluation.

4.2. Predicting O. & S. Costs

Recent proposals have been made for the generation of a parametric approach to predicting future O. & S. costs. This approach has, in our opinion, several defects:-

- It is expensive for an operator to collect data and for the contractor to process this data.
- Such data is only a picture of the past and peculiar to the circumstances which generated it.
- It is of little use in assessing the implications of proposed changes in performance requirements, logistic procedures or technological advances.

4.3. Analytical Prediction of O. & S. Costs

As a consequence of these limitations Rolls-Royce has looked for a more dynamic analytical tool and is developing a group of systems which can be used by both the contractor and the operator. The system uses the interaction between the physical characteristics of an engine, the environment specified and the proposed logistic system; these being the main drivers of O. & S. costs. The flow chart of this system is shown in Fig. 7.

Failures of primary parts and modules are predicted from technical data and the possibilities of secondary damage assessed at the module level. The life assumptions and secondary damage matrices are used in a computer simulation of flying the fleet of aircraft over the life of the type. Failure incidents are generated by random number selection and only engines which survive to the hard life of the lowest lifed module are shown as scheduled removals. The outputs from this system are:-

- Cost of parts fitted to engines
- Repair and overhaul maintenance manhours and costs
- Spare engine and spare module investment

The cost of parts fitted to the engine is determined by:-

- Major component life predictions
- Casualty rates

The interaction of these two elements results in parts failure distribution. Prediction of component life limitations relates failure modes (creep, thermal and low cycle fatigue, coating degradation etc.) to mission profiles operating climatic conditions and engine rating. Historic data is used in the assessment of secondary damage characteristics and the effect of erosion and foreign object damage brought about by a particular operating environment.

Repair and overhaul maintenance manhours and costs are the summation of:-

- Organisational level maintenance, which is primarily preventative maintenance involving scheduled inspections laid down by the contractor and unscheduled maintenance, (see Figs 8 and 9), changing of line replacement items and changing complete engines.
- Intermediate and depot level maintenance involving module changes and repair and overhaul of engines as required by specific engine and logistic systems.

The spare engine and spare module investment is determined by:-

- The parts failure distribution
- Premature engine and module removal rate

- Logistic cycles

Policy decisions for the minimum hours left on undamaged adjacent modules during engine removal for module change and overhaul/repair decisions points are also built into the simulation which results in an Engine and Module Arisings Forecast (see Fig. 10). In conjunction with these forecasts the logistic cycle determines the size of the pools of spare engines and spare modules. A typical example of a logistic cycle for a light strike/trainer aircraft is shown in Fig. 11.

4.4. Estimation of Other O. & S. Costs

A major O. & S. cost driver is fuel. Fuel costs are dependent upon the engine performance, the aircraft aerodynamics, stores loading, mission mix, rate of flying and force strength, and can be readily computed,most effectively by the aircraft constructor in conjunction with the engine manufacturer. Other O. & S. costs to be considered are:-

- Ground Support equipment
- Maintenance tooling
- Training
- Technical publications
- Stores stock

The costs of which can be estimated by standard methods.

4.5. System Capability

All of these elements come together to form the total cost of ownership of the engine. Rolls-Royce believe that sensible assessments can be made of the many variables that are involved and believe that the system outlined here offers the best way of making an estimate of the basic life cycle cost of an engine and comparative evaluation of proposals for engineering changes, changing in mission profile and operating procedures.

5.0. RB.401 LOW COST DESIGN

Some of the results of applying these procedures became effective during the design of the RB. 401 engine (see Fig. 12) aimed at the new generation of business aircraft, military trainers and light strike aircraft. (See Fig. 13).

To be competitive throughout the 1980s and 1990s the design must provide for a good balance between the various requirements for low fuel consumption, low noise, low exhaust emissions, low cost of ownership, low weight and minimum technical risk. These considerations lead to a conventional straight flow configuration using axial compressors and turbines readily adaptable for a variety of civial and military derivatives. (See Fig. 14). In the 07 versions shown here, the take-off thrust is 5,500 lbs, by-pass ratio 4·2:1 and the cruise pressure ratio 16·4:1. Throughout the design every effort was made to keep the number of parts down, not only by taking advantage of demonstrated technological development but also by applying Value Engineering techniques.

5.1. The Fan Assembly

The fan has low aspect ratio titanium blades without mid span dampers, which would have increased cost. Dovetail root fixings are used to attach the blades to a forged, simple profile, disc. The disc and blade assembly can be removed from the front of the engine without disturbing any other major components. Individual damaged blades can also be removed without disturbing the disc or nose cowl, balance being maintained by replacing blades in matched pairs. This solution gives a robust fan with a small number of blades and an optimum balance of cost and weight. The blade containment shroud is made from flash welded rings and is located immediately over the fan blades and extends rearwards to the fan exit stators which are manufactured from strip material. The profile of the nose cone minimises ice accretion and eliminates the need for nose cone anti-icing, giving cost and performance benefits.

5.2. The H.P. Compressor Assembly

The H.P. compressor performance is based on one of a family of research compressors on which over 400 hours of rig operation had been accumulated. The aerodynamic objectives of high stage loading, efficiency and handling have been achieved with moderate blade speed giving high component lives. The non-variable stator blades are made from extruded nickel alloy strip, stabbed and brazed into a liner mounted within the compressor casing. This construction also provides an effective method of controlling tip clearance over the full range of operating conditions. The rotor blading is Electro-Chemically Machined from titanium bar stock and sized in groups in the interests of cost saving. For instance, the sixth stage rotor blade is a

cropped fifth stage and the seventh and eighth are identical.

A number of construction techniques were examined for the compressor rotor, including centrally bolted and welded disc configurations, finally shortlisted to rim bolted and combined disc/drum, with steel and titanium as alternative materials in each case.

There was good background experience of the rim bolted construction (see Fig. 15) since it is used in the Olympus 593, the disc forgings are simple and the torque is taken through a second skin protected from the gas path temperature. However, there was a 10,000 cycle life limitation in titanium compared with 25,000 cycles from steel discs. In terms of usage 10,000 cycles is approximately 17 years of business usage or five years of commercial commuter usage.

The combined disc/drum construction (see Fig. 16) has fewer parts, is simple to assemble, blade changes are particularly easy. However, the behaviour of circumferential blade roots was unknown to Rolls-Royce. The driving torque is taken through the rim and it is not easy to introduce disc modifications.

A weight and parts cost analysis (see Fig. 17) showed that not only was the titanium disc/drum cheaper than the steel rim bolted construction but it was considerably lighter. The comparative life cycle cost of the disc/drum and rim bolted rotor assessed (see Fig. 18) on the basis of cost of replacement against warranty life, again the disc/drum titanium rotor appeared to be the most attractive solution and has been adopted.

5.3. The Combustion System Assembly

The combustion system is of the vapourising type used on many Rolls-Royce engines, with 16 'T' shaped tubular vapourisers fed by simple forged burner feed pipes having a comparatively large metering hole and no complex sprayer head. A major cost saving feature is the use of cooling rings manufactured from sheet or strip material. Fig. 19 shows a cooling ring machined from a forging with conventionally drilled cooling holes. In the sheet metal version the holes are Electron Beam Drilled. This configuration gives a more efficient

cooling film and the internal skirt, which can cause problems in service, can be deleted. Due to improved material utilisation and consequent reduction in machining, the cost of the complete combustion chamber has been reduced by over 50% compared with a forged cooling ring design.

The combustion chamber outer casing is manufactured from a sheet pressing welded to high material utilisation flanges. As with all the major casings it has a turned profile with boss locations for such services as Borescope Inspection, Burner Feed Pipe Mountings confined to bands which are Electro-Chemically Machined in one pass.

5.4. The Turbine Assembly

Successful H.P. turbine blading design is crucial if Operating and Support costs are to be minimized, since it can contribute over 30% the parts replacement cost. The blades have a relatively thick aero foil section, which is resistant to damage and into which effective cooling air passages can be easily cast. Most of the blade is finished as cast (see Fig. 20) machining is only necessary for the root form, the tips of the shroud sealing fins and abutment faces. There is a generous gap between the H.P. turbine and the first stage L.P. nozzle to minimise secondary damage in the event of a partial or complete H.P. turbine blade loss.

The L.P. turbine is a conventional two stage design with fully shrouded blade tips. Contra rotation of the two main shafts considerably reduces the gas deflection and permits the use of nozzle guide vanes with a relatively short axial chord which, whilst still enabling the bearing supports to pass through, effectively shortens the casing and shafts. The attachment of the L.P. turbine disc assembly to the shaft is similar to that used for the H.P. turbine disc and the fan disc. In each case the disc is located on three equi-spaced interference fit splines and secured with a nut locked by a friction ring. The L.P. shaft is unflanged permitting high material utilisation and, since it is unchambered, it can be through bored. This type of disc mounting together with the adoption of an inter-turbine bearing has a major maintainability benefit, by enabling rapid hot end strip. Fig. 21 shows the times now being achieved.

5.5. Health Monitoring

Transducers are sited to respond to main rotor structure vibrations

(see Fig. 24) and will thus provide an early indication of any mechanical malfunction in the rotating system. Magnetic plugs and sample facilities in each of the oil systems scavenge return line provides full monitoring capability. Radio isotope inspection can be carried out by removing the nose cone and passing the probe through the shaft.

5.7. Bearings and Bolts

The RB.401 has a simple bearing arrangement where each of the two rotating assemblies is mounted on identical ball and roller bearings. These four main bearings are grouped such that there are only two oily spaces in the engine, with consequent simplification of the sealing arrangements. Finally, a minor point but an indication of the importance that has been paid to details, the parts list shows that a total of 350 bolts is required to build the engine made up from 23 part numbers, the majority of which are from the standard AS series.

6.0. CONCLUSION

Full evaluation of the effectiveness of these techniques in reducing Initial and Life Cycle Costs will have to await the test of time. However, it is possible to identify some significant pointers from the RB.401 programme so far.

There have been relatively few manufacturing or inspection problems. The engine has proved to be extremely easy to build and went to test on schedule. It has since achieved brochure performance, and the mechanical record is good. This, we feel, is due in equal part to the use of previously demonstrated technology and the simple to make, easy to check and, therefore, repeatable parts that have resulted from the constant production/design liaison activities.

The cost/achievement curve is within the very highly constrained budget confirming our belief that the application of low cost design techniques can reduce cost in both the development and the operational phases of an engine's life cycle.

--ooOoo--

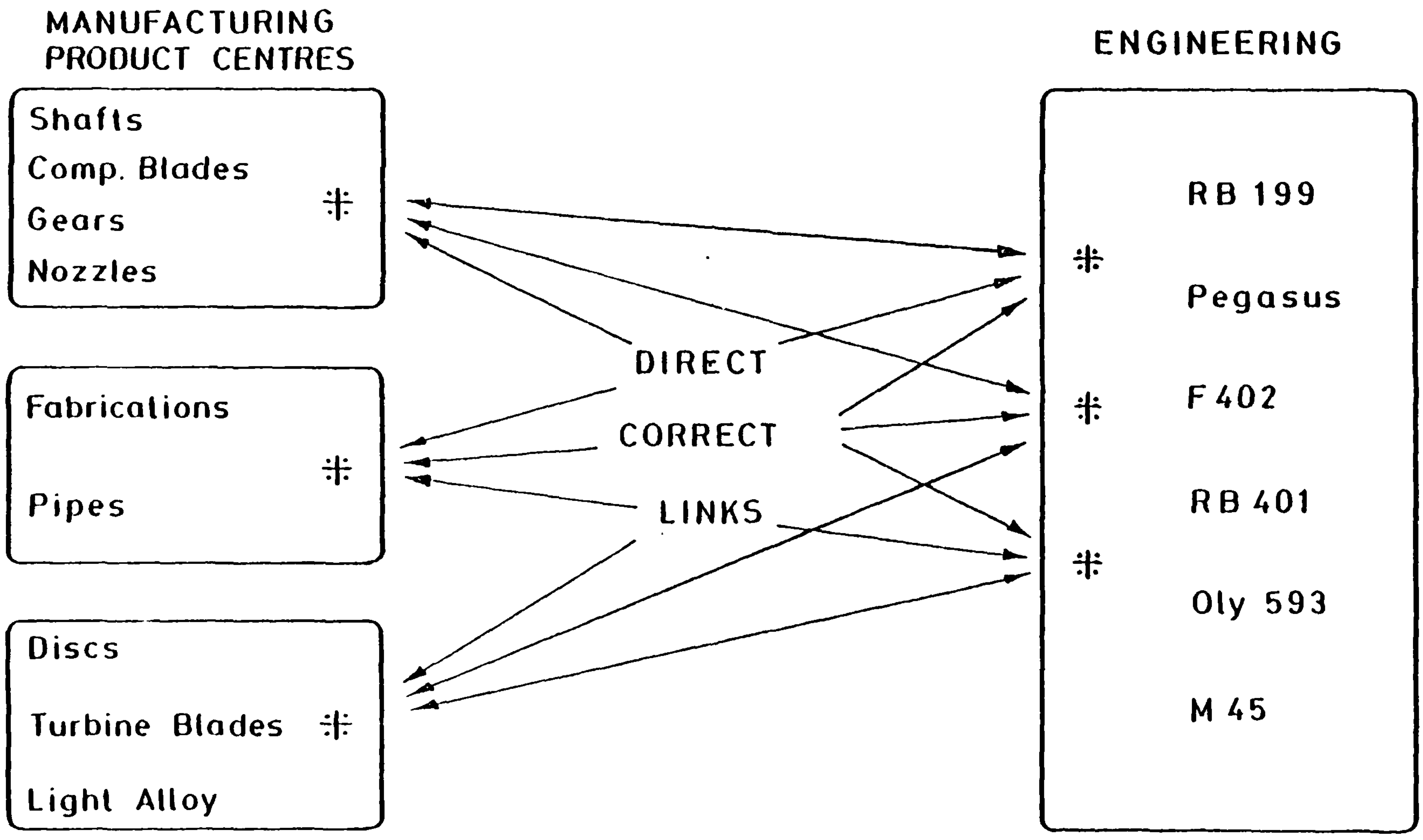

Fig. 1 Function of Manufacturing Design Liaison Engineers

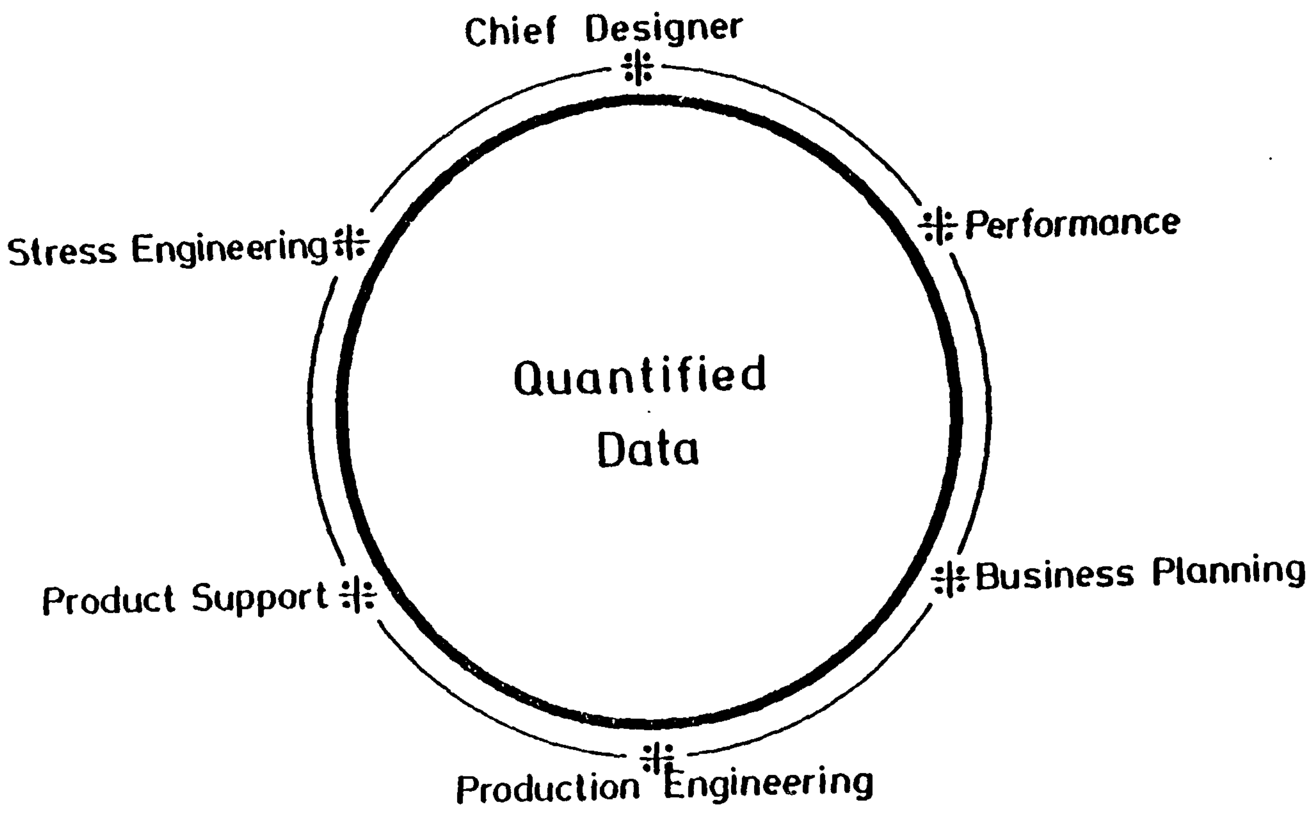

Fig. 2 RB401 Design Management Style

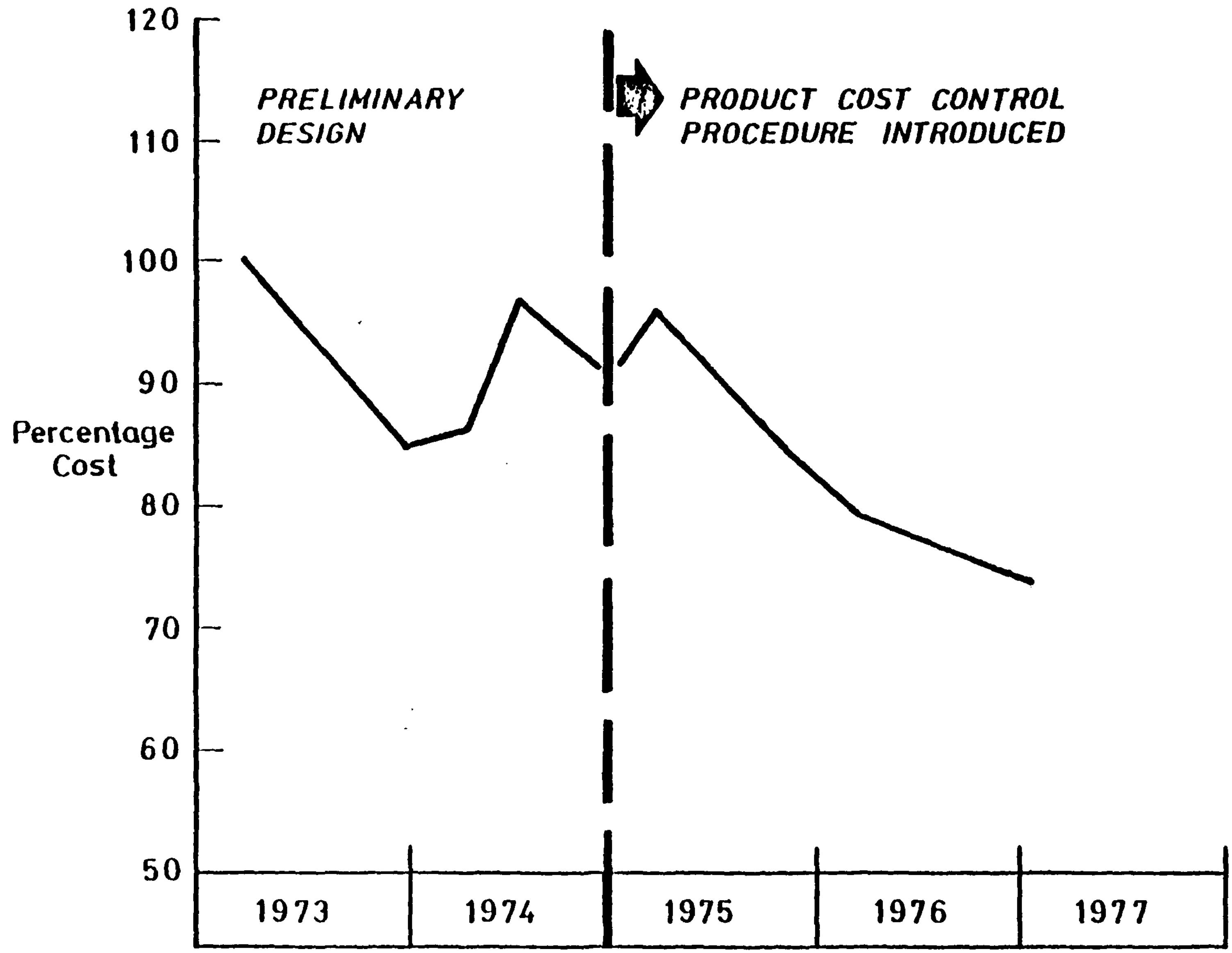

Fig. 3 RB 401 Reduction in Factory Cost

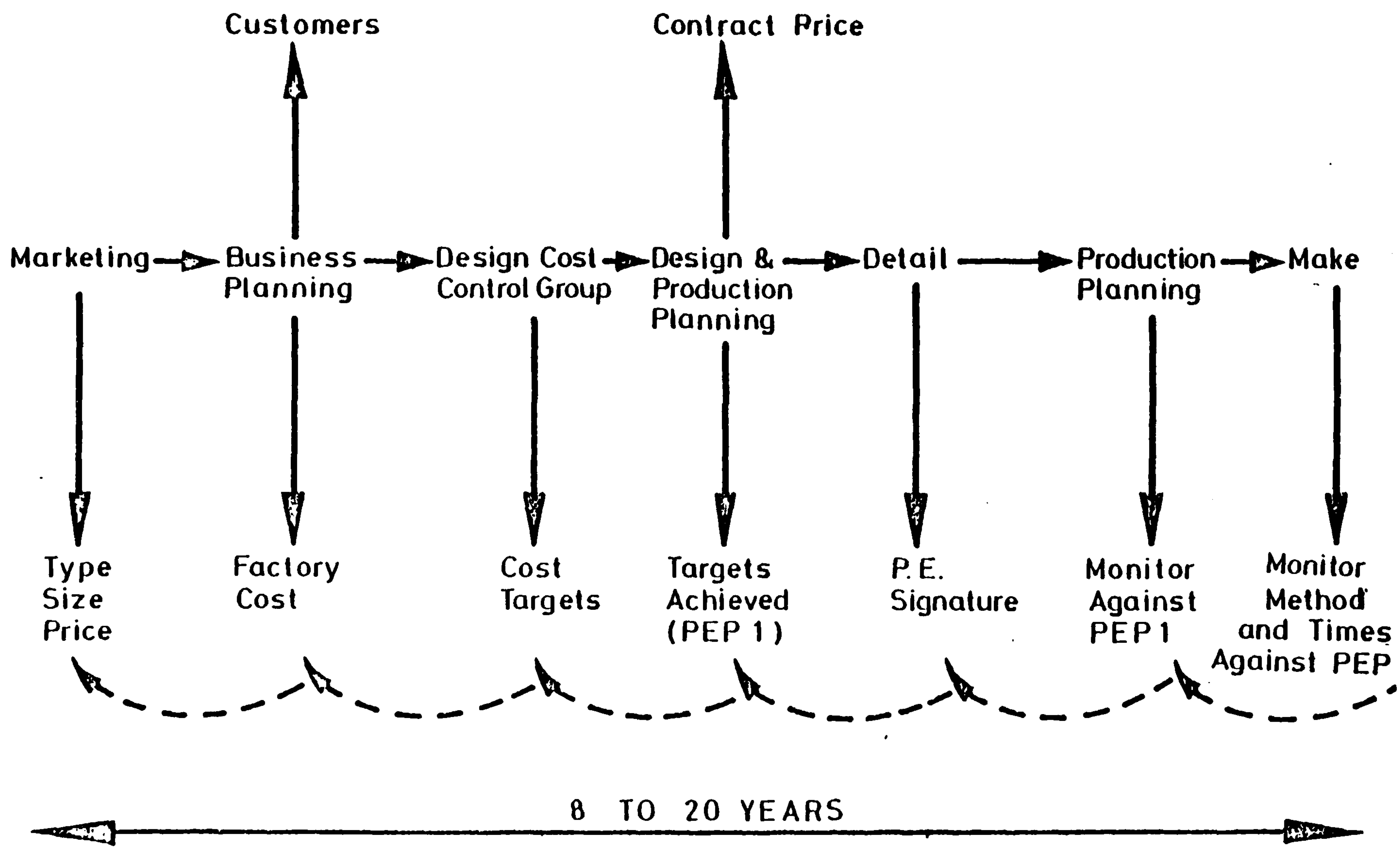

Fig. 4 Product Cost Control Procedure

PEP. 1	COMPONENT COST DATA					REF Nº A. 113
ENGINE RB 401-07	MODULE L.P. TURBINE	A SHEET —	SCHEME Nº JFS1035	ISSUE A	TITLE L.P. DRIVE SHAFT	SUPPLY RESPONSIBILIT PATHWAY

PURPOSE

TO PROVIDE COST ESTIMATE FOR RB401-07 PROFIT PLAN

INFORMATION TO BE USED FOR ESTIMATE

GENERALLY AS EA907121 (EX MASH) FOR TOLERANCES, SURFACE FINISH, TREATMENTS ETC

EXISTING	
MATL £	
STH	
SA(BOF)	
DV	

OVERALL PROGRAMME AND RATE

1000 ENGINES 10 SETS/MONTH

PRODUCTION ENGINEERING COMMENTS (EG. EFFECT OF DESIGN ON YIELD, DAY VALUES ETC.)

Estimate based on availability of Craven Boring M/c.

Minimum metal removal for balancing assumed.

SPECIAL PLANT	
£	
TOOLING	
£ 20,000	
SETTING	
48 HRS	

	TARGET	ESTIMATE
MATL	£ 450	£ 400
STH	22	25
DAY VALUES		8

DESIGN COST CONTROL GROUP	REQUESTED BY	DATE	APPROVED BY	DATE	SHEET Nº
	M.C. Russell	30.6.75	R.D. Keitch	7.7.77	1

Fig. 5 Production Estimate Enquiry

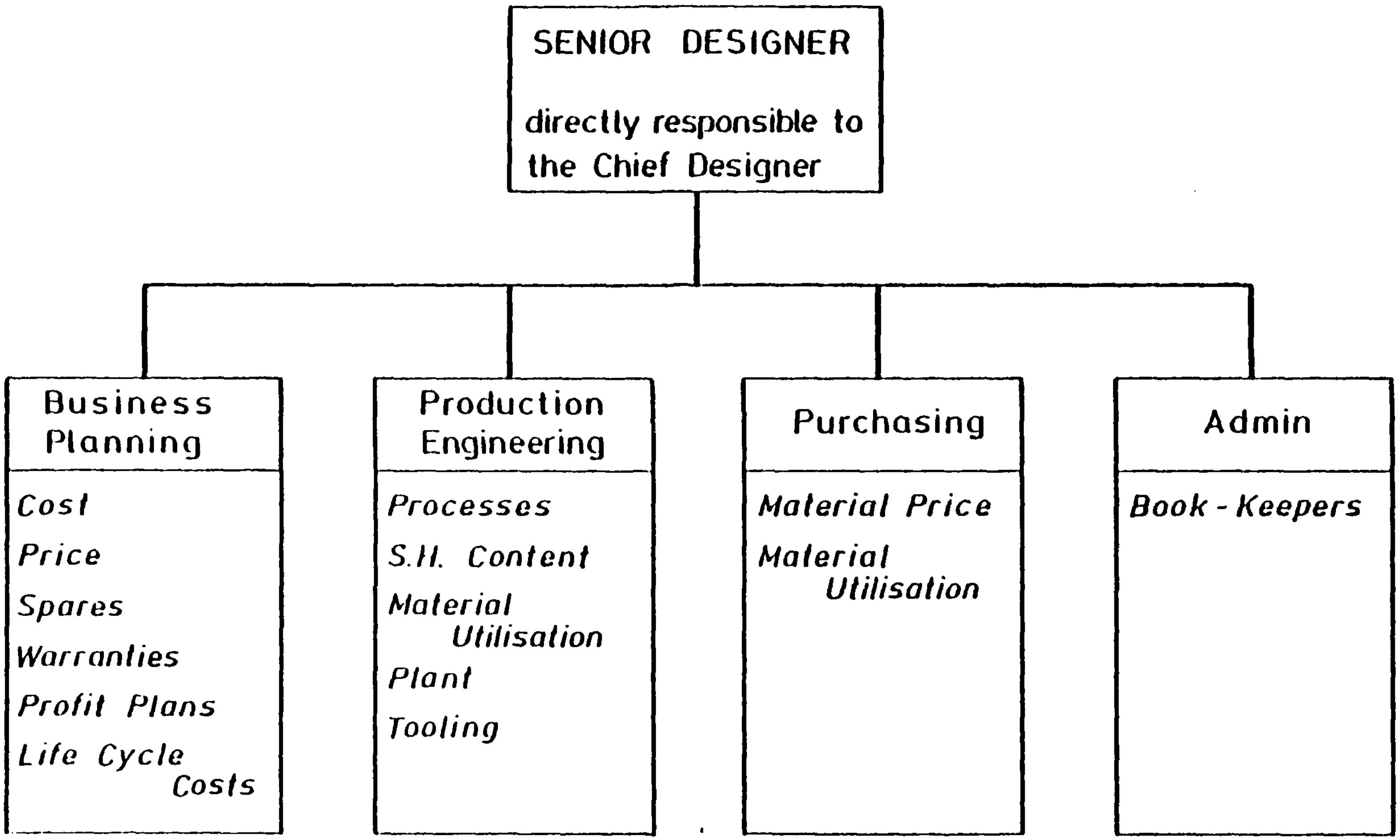

Fig. 6 Design Cost Control Group

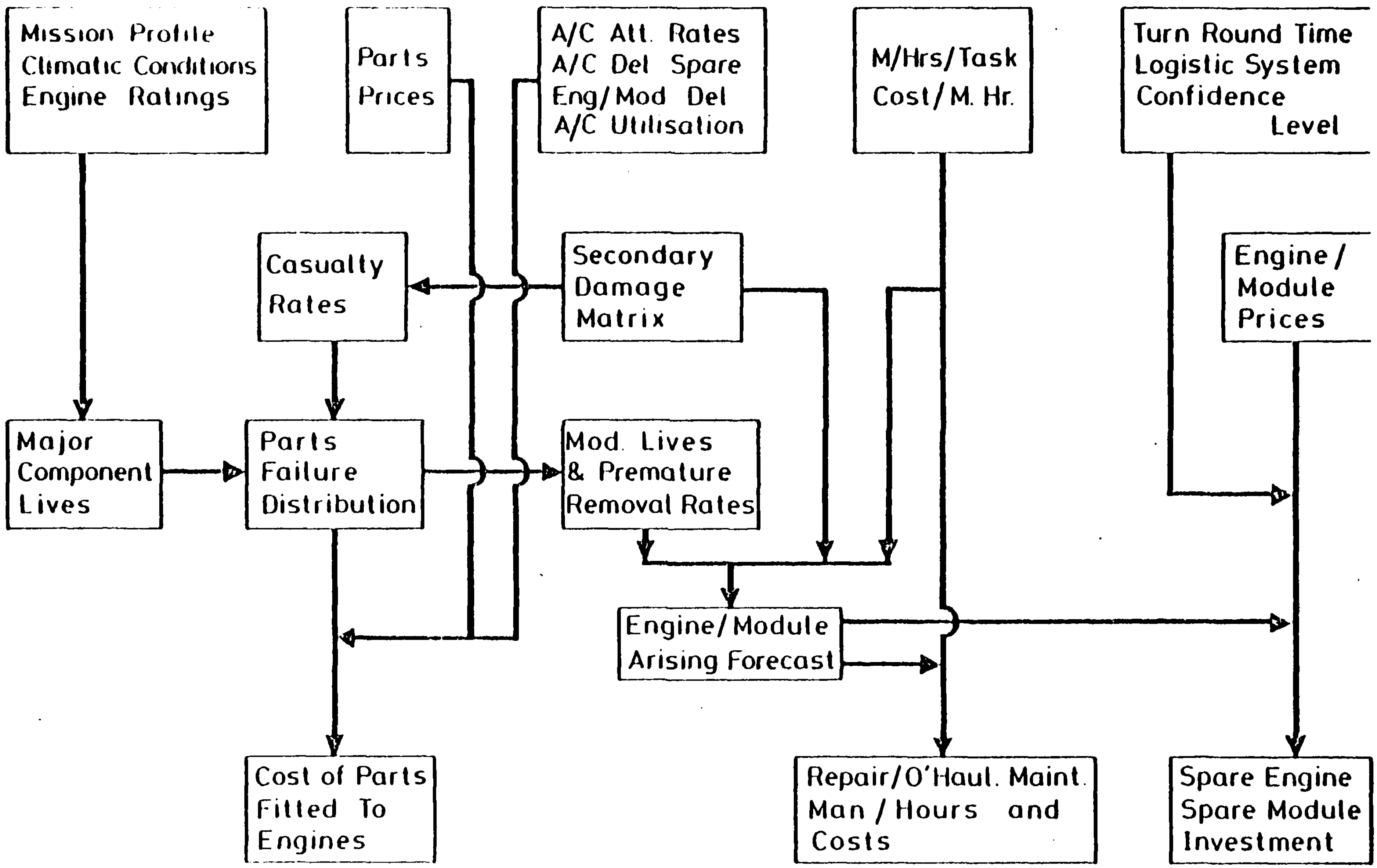

Fig. 7 O & S Costs Analysis Flow Chart

TYPICAL SCHEDULED ORGANISATIONAL LEVEL MAINTENANCE LABOUR FORECAST

TASK	SINGLE		
	Frequency /1000 Hrs	MMH	MMH/1000 Hrs
ECU Installation			
- Turnaround Inspection	675	.1	67.5
- Daily Inspection	350	.15	52.5
Engine Oil System			
- Oil Replenishment	350	.15	52.5
- SOAP Sample	50	.10	5.0
- Magnetic Plugs	50	.15	7.5
Engine			
- Borescope - Hot End	5	1.0	5.0
- Borescope - Cold End	5	1.0	5.0
- Visual Inspection of Fan	100	.15	15.0
ECU			
- Zonel Inspection	5	1.0	5.0
TOTAL MMH/1000 Flight Hours			214.0

MMH - Maintenance Manhours
FH - Flight Hours

SOAP - Spectorgraph Oil Analysis Procedure
ECU - Engine Change Unit

FIG. 8

TYPICAL UNSCHEDULED ORGANISATIONAL LEVEL MAINTENANCE LABOUR FORECAST

COMPONENT	SINGLE		
	Frequency /1000 Hrs	MMH	MMH/1000 Hrs
Fuel Control Unit	.3	3.0	.90
LP Fuel Pump	.15	1.5	.225
Fuel Filter	.1	.5	.05
Filter Differential Pressure Switch	.2	.5	.1
T_J Limiter Amplifier	.3	1.0	.3
T_J Thermocouples	.25	2.5	.625
HE Ignition Unit	.3	1.0	.3
HE Ignition Plug	2.0	.5	1.0
Blow off Valve	.15	1.5	.225
N_1 Speed Probe	.15	.75	.113
N_2 Speed Probe	.05	.5	.025
Turbine Cooling Thermocouples	.3	1.25	.375
TCA Amplifier	.2	.75	.15
Vibration Transducers	.2	.75	.15
Magnetic Oil Dipstick	.2	.5	.1
Oil Cooler	.05	1.25	.063
Low Oil Pressure Switch	.20	.5	.1
TOTAL			4.801

FIG. 9

TYPICAL TRAINER FLEET - ARISINGS FORECAST

YEAR	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Engine Hours x 100	4088	31155	61568	104670	143340	170695	194400	194400	194400	194400				
Engine Removals														
- Scheduled	3	28	62	103	120	162	178	206	214	210				
- Unscheduled	5	26	66	99	134	174	187	187	191	184				
- Total	8	54	128	202	254	336	365	393	405	394				
Module Throughput														
1. Fan	1	4	9	14	21	25	26	25	29	26				
2. Intermediate Csg	-	3	5	8	12	17	16	17	17	17				
3. Gearbox	-	2	2	5	7	9	10	8	11	10				
4. HP Compressor	1	5	16	19	30	42	42	40	43	40				
5. Comb. Chamber/HP NGVs	1	5	28	63	68	58	97	103	150	118				
6. HP Turbine	4	43	130	171	142	187	217	235	213	226				
7. LP Turbine	1	4	10	23	31	38	39	43	40	43				
8. Exhaust Annulus	1	6	14	15	22	28	28	31	31	27				

FIG. 10

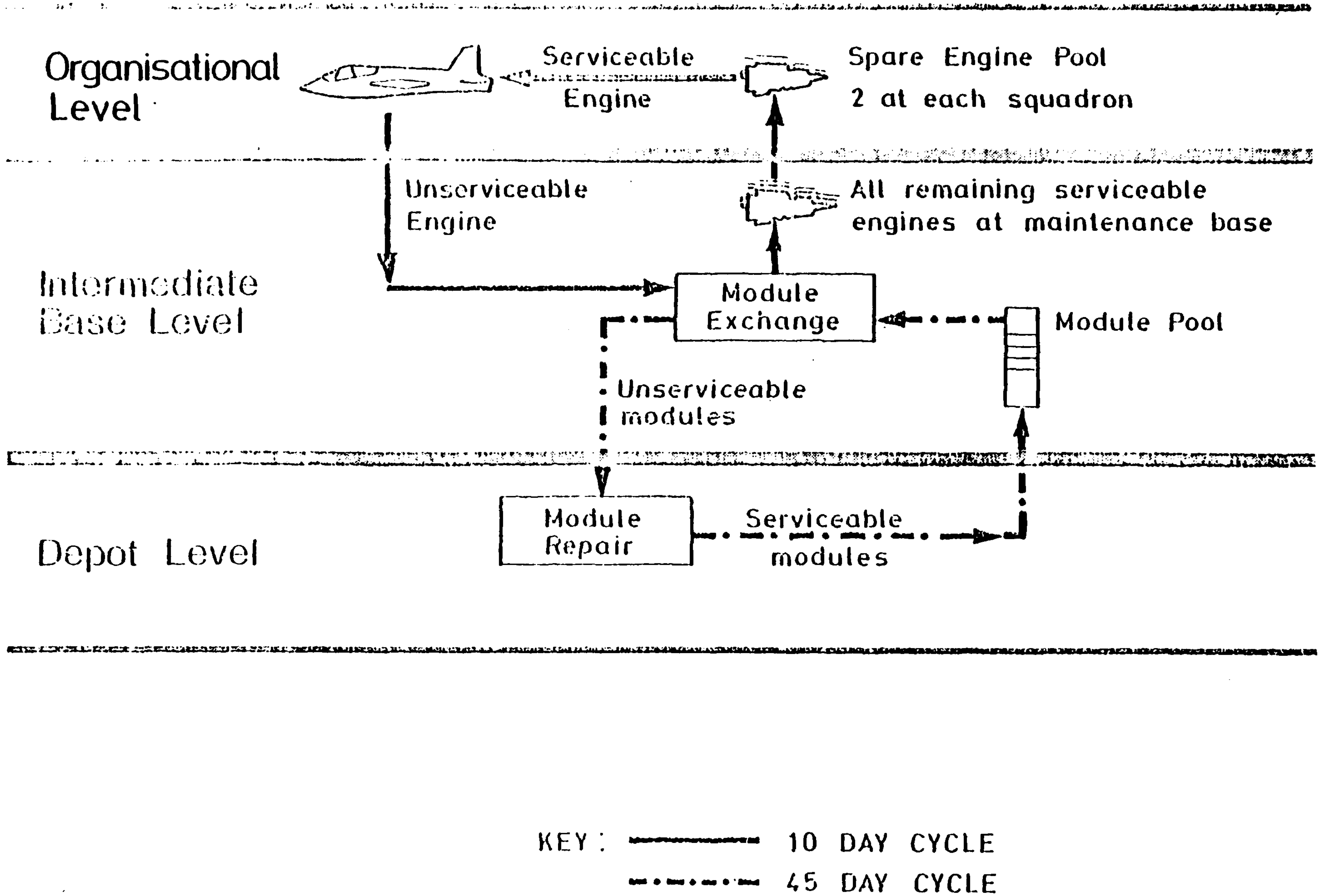

Fig.11 Logistic Cycle For Modular Engine. Light Strike / Trainer Aircraft

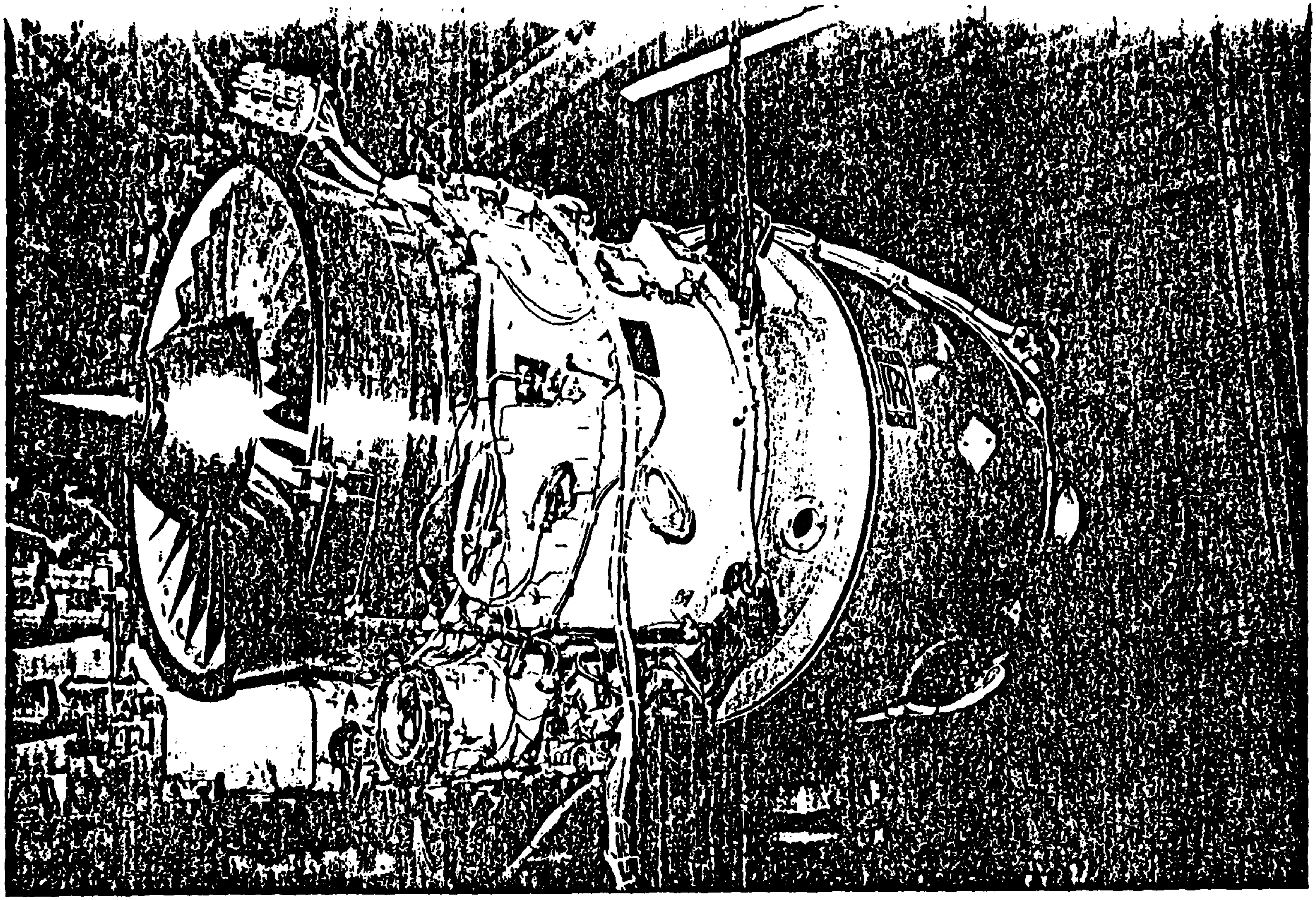

Fig.12 EXTERNAL PHOTO RB401 ENGINE

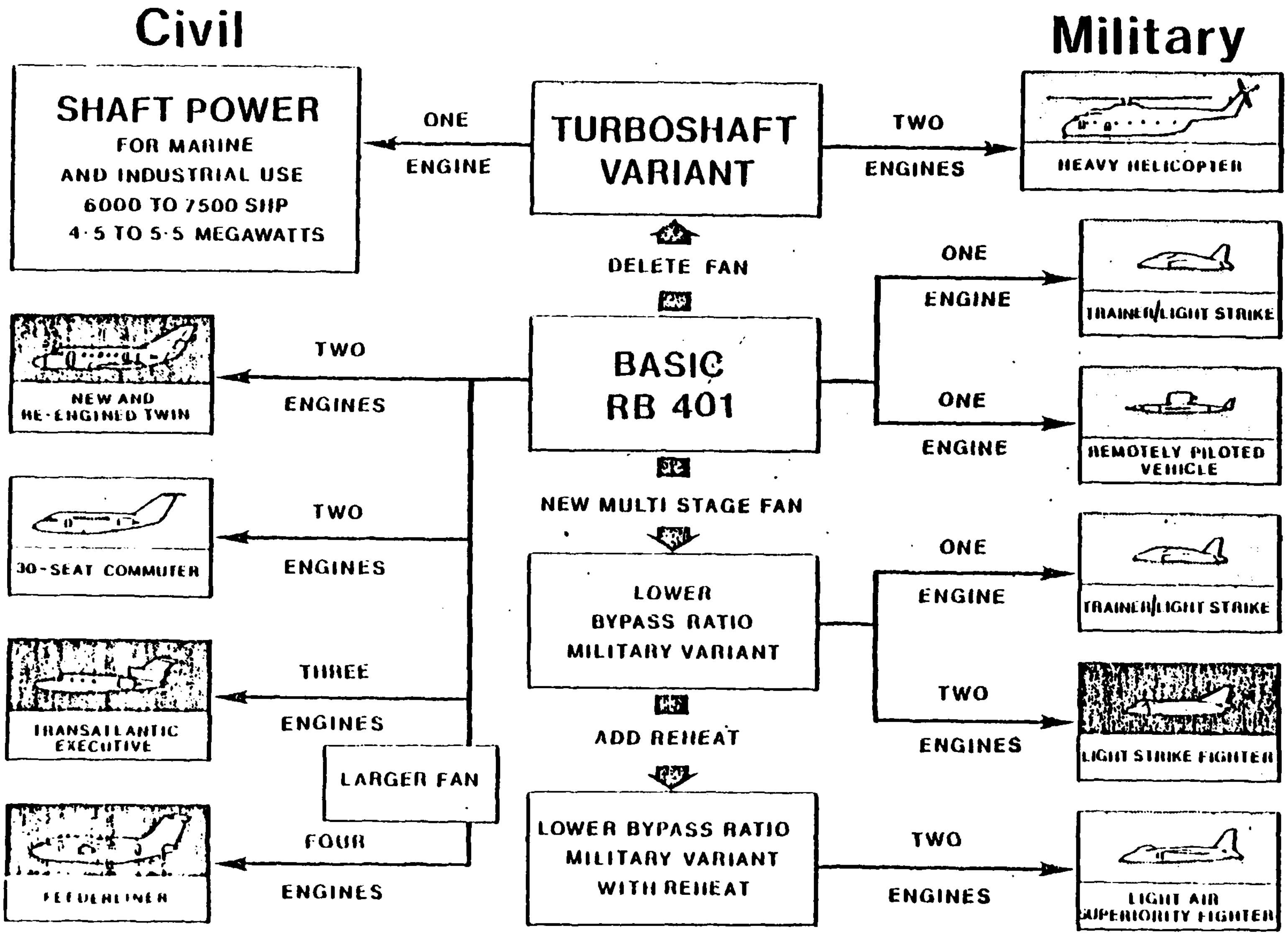

Fig. 13 RB 401 APPLICATIONS

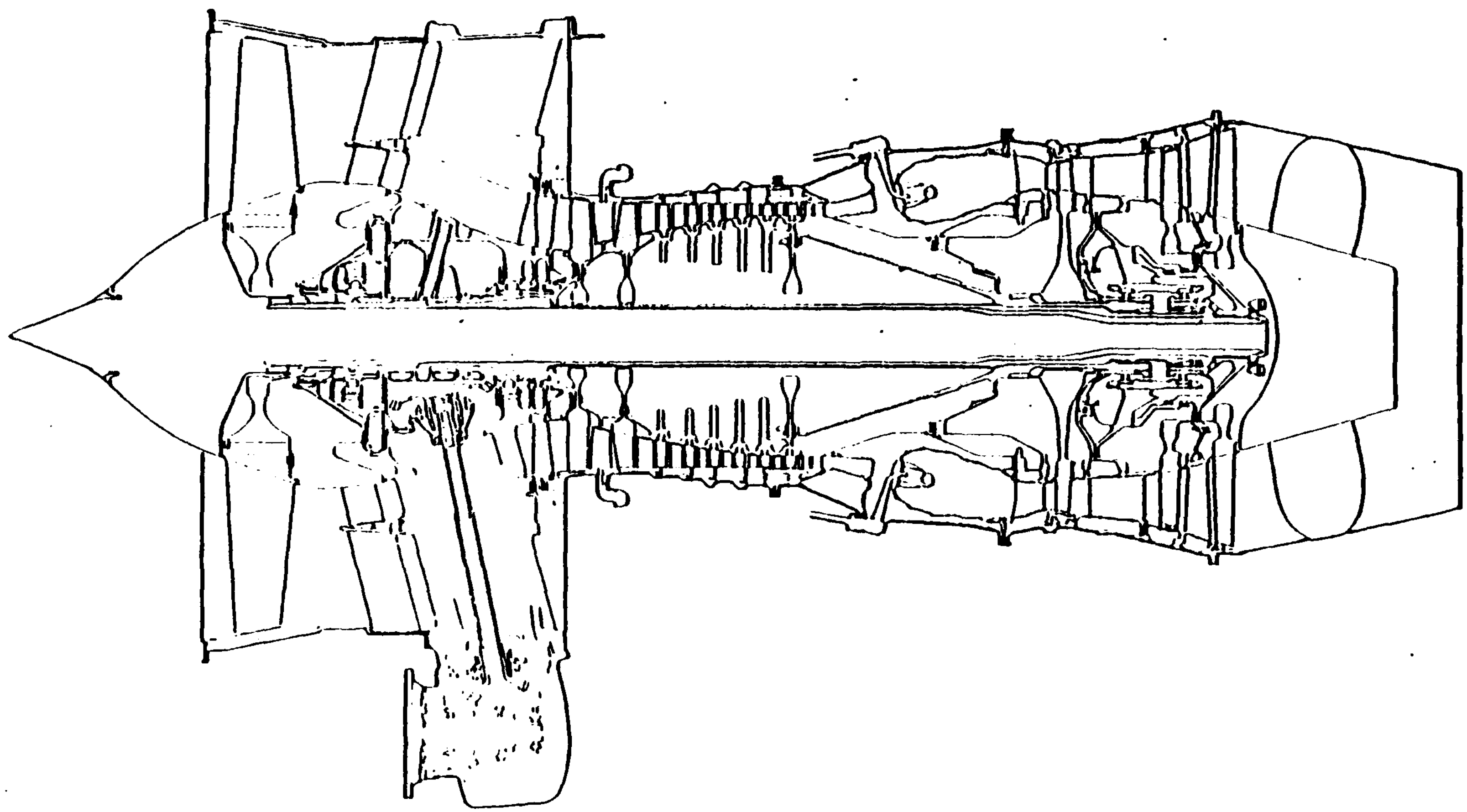

Fig. 14 RB 401 General Arrangement

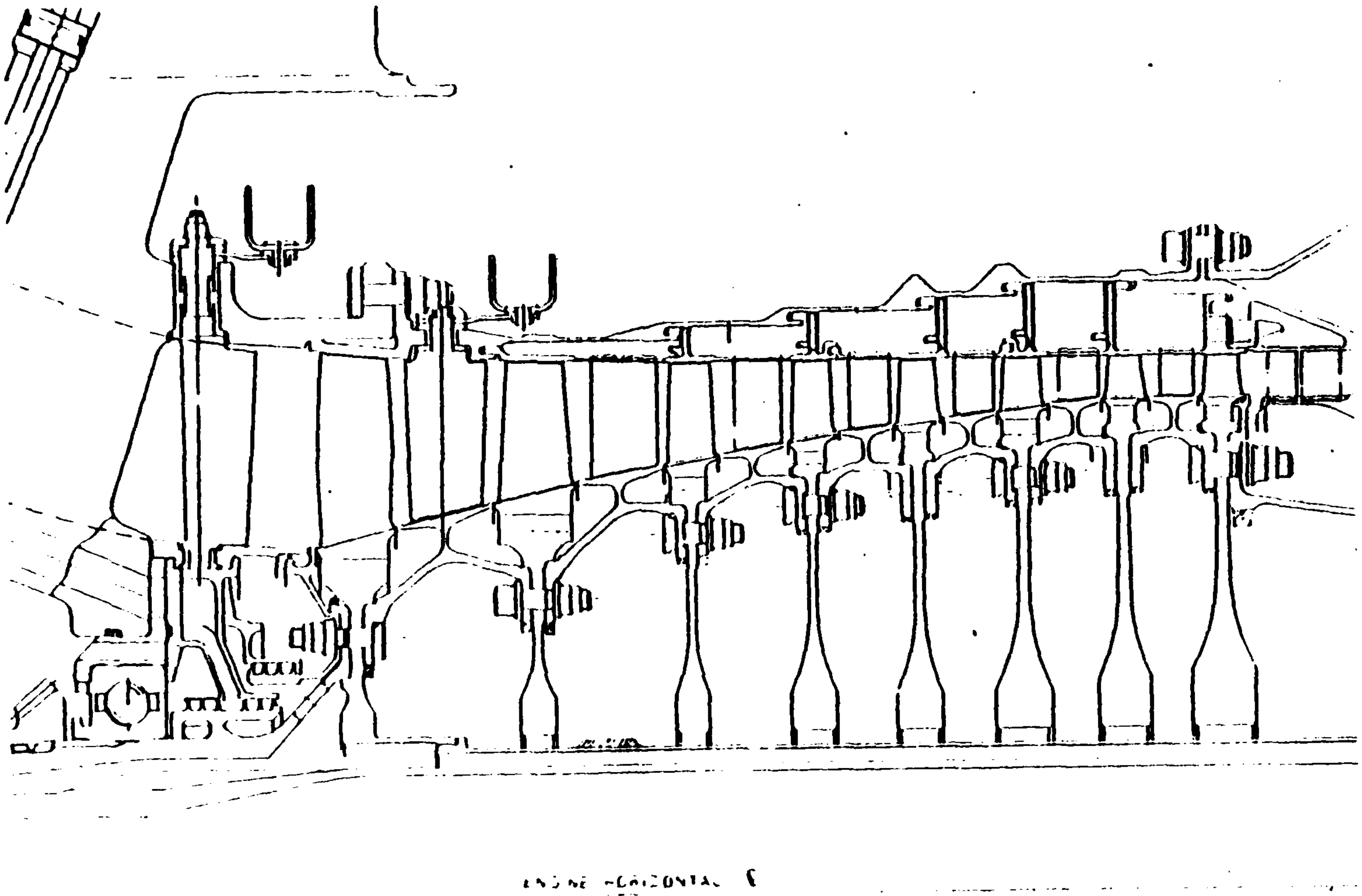

Fig. 15 H.P. Compressor Configuration - Rim Bolted

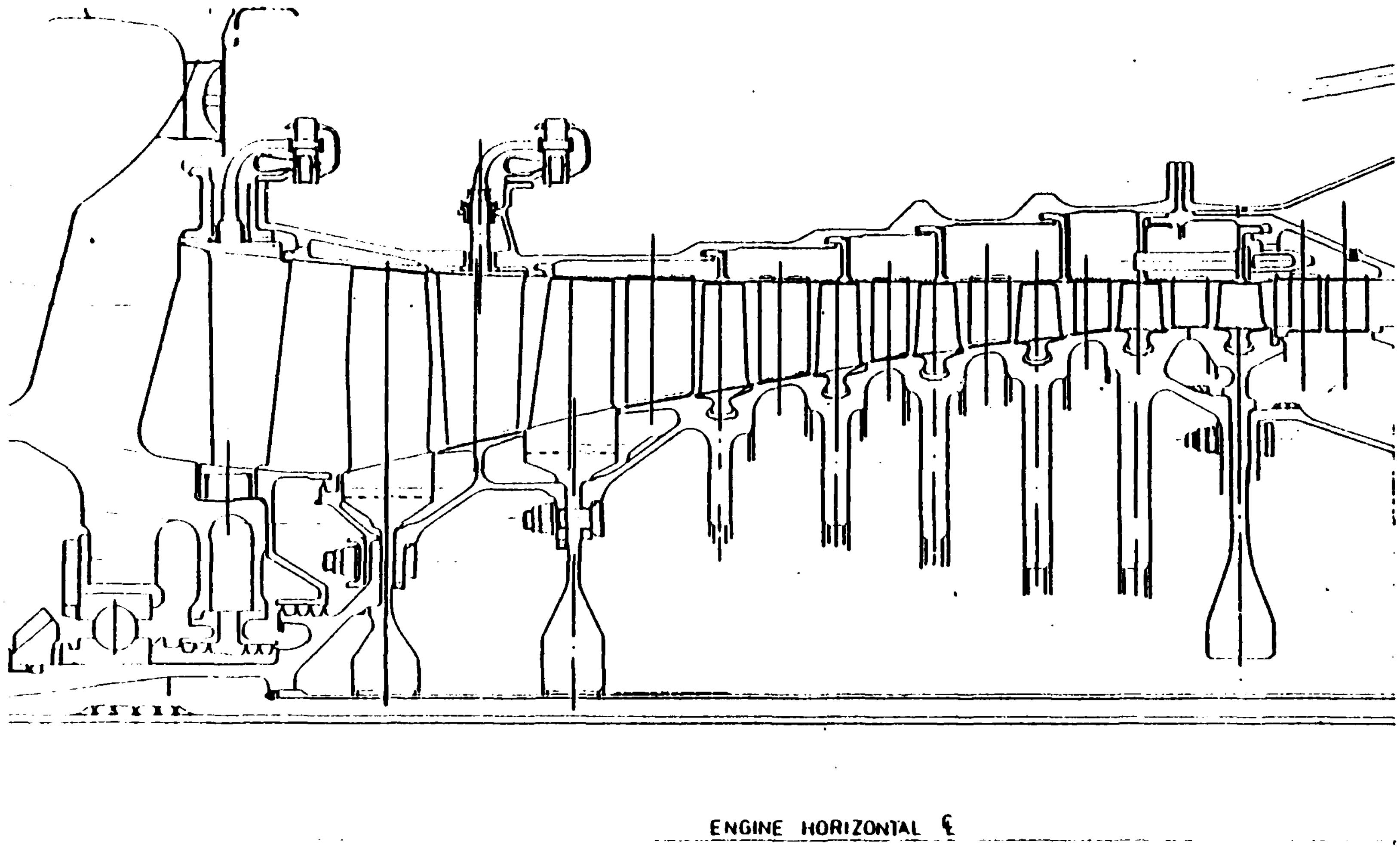

Fig. 16 H.P. Compressor Configuration – Combined Disc/Drum

		WEIGHT (LB)	COST (RATIO)
Rim Bolted	Steel	130	1·13
Rim Bolted	Titanium	108	1·22
One Piece Drum	Steel	125	1
One Piece Drum	Titanium	98	1·01

Fig.17 H.P. Compressor Rotor - Comparative Weights and Costs

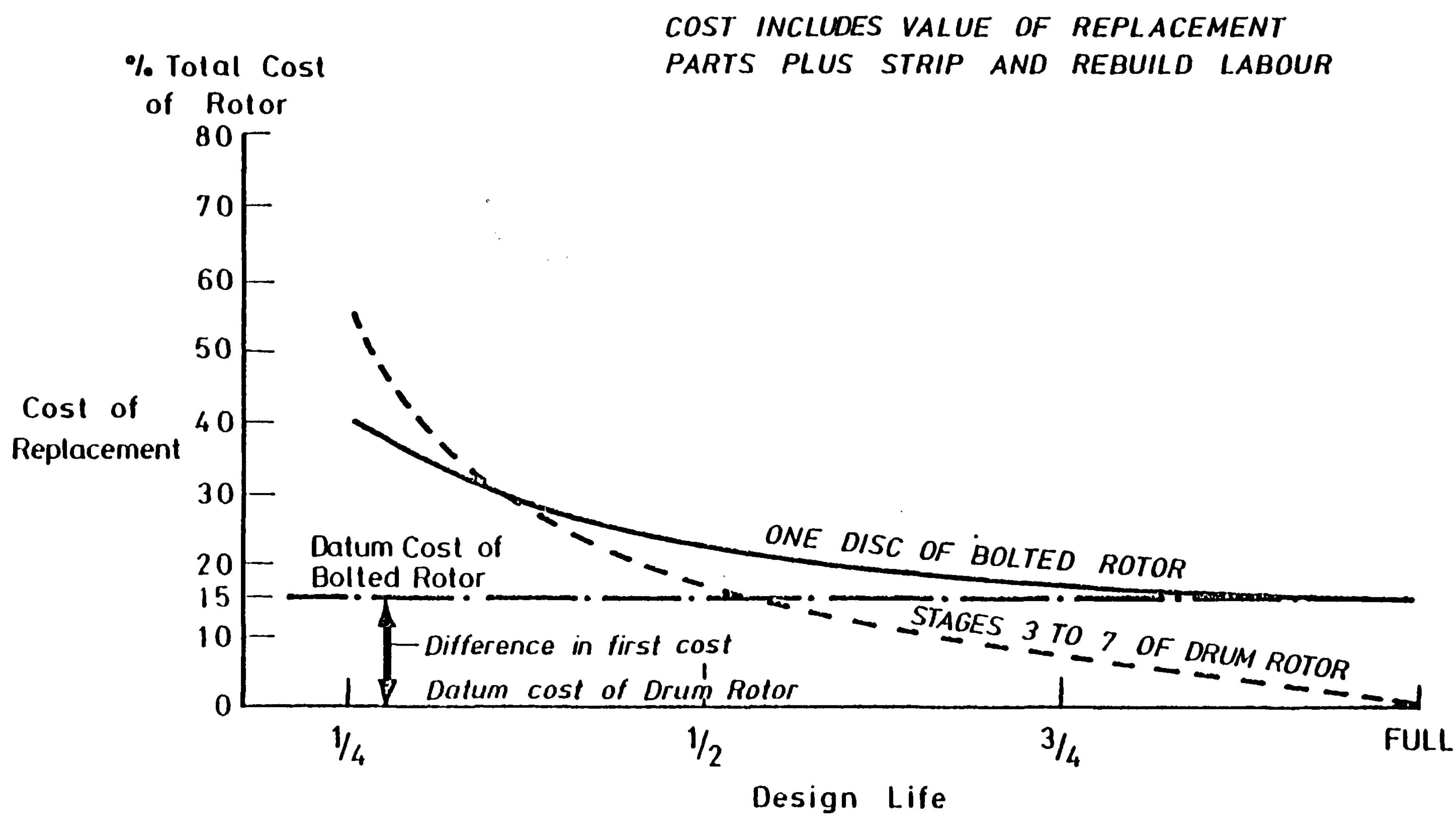

Fig. 18 H.P. Compressor Rotor - LCC Comparison

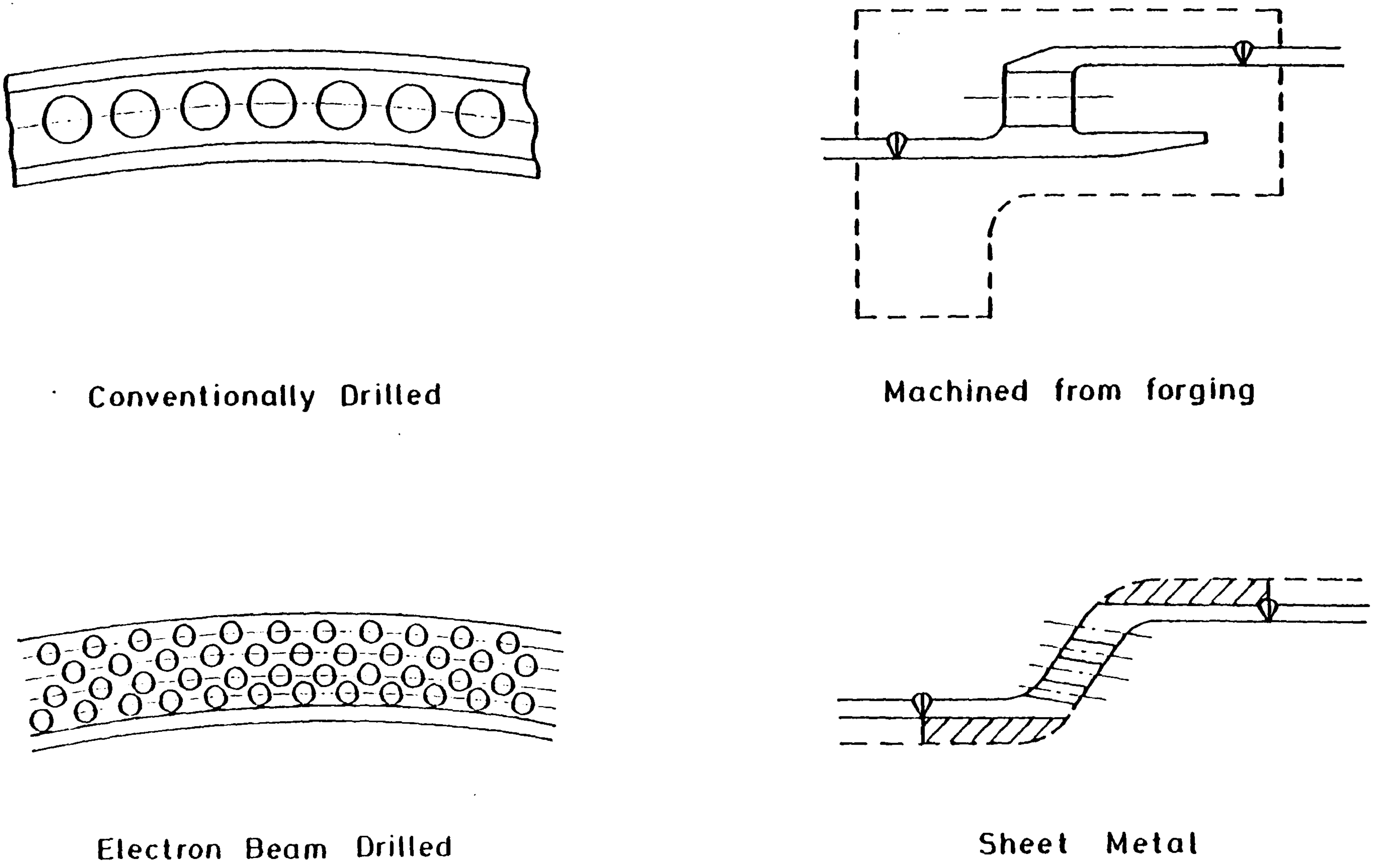

Fig. 19 Combustion Chamber Cooling Rings - Designs

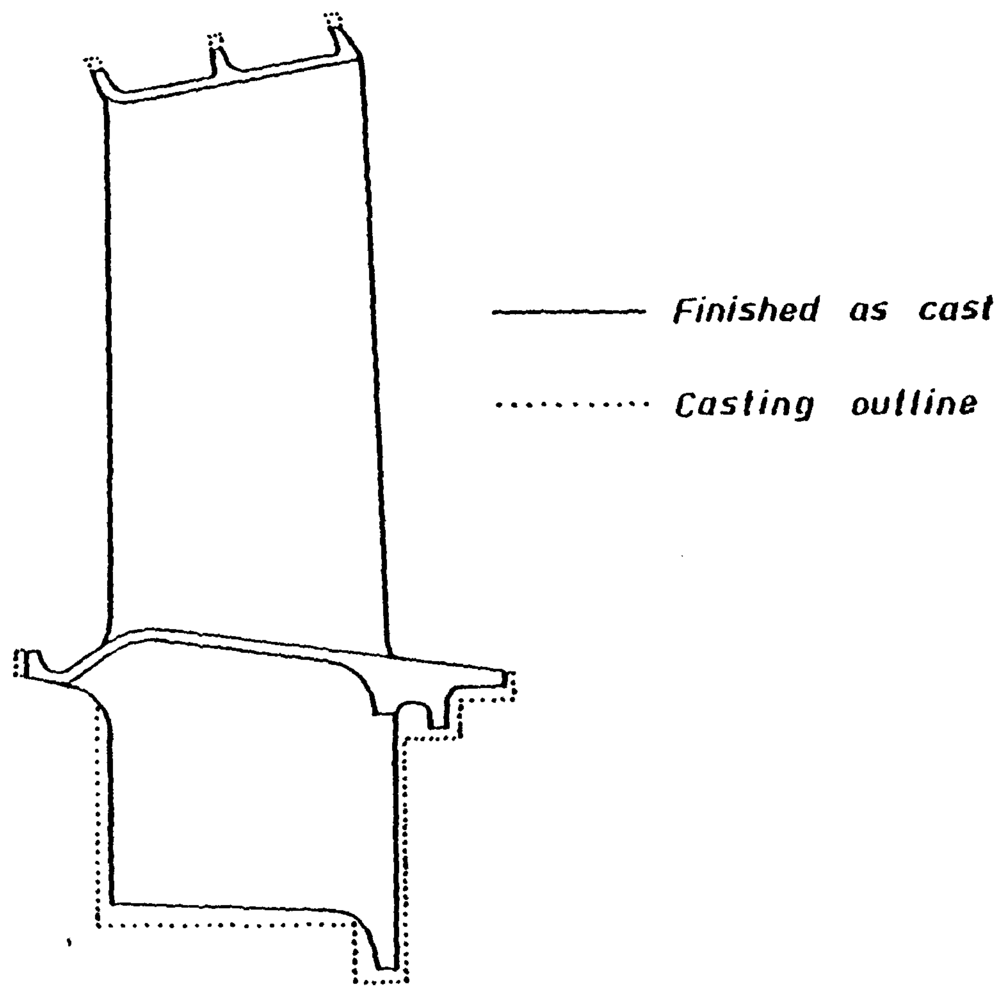

Fig. 20 H.P. Turbine Blading - Machining Requirements

2 MAN OPERATION	HOURS
REMOVE L.P. TURBINE	*0·5*
REMOVE TURBINE CASE	*1·0*
REMOVE H.P. TURBINE DISC	*1·5*
REMOVE COMBUSTION CHAMBER AND CASING	*1·5*
STRIP COMBUSTION CHAMBER	*2·0*

Fig.21 Achieved Hot End Strip Times

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PROCEEDINGS OF OSD AIRCRAFT ENGINE DESIGN & LIFE CYCLE COST SEM--ETC(U)
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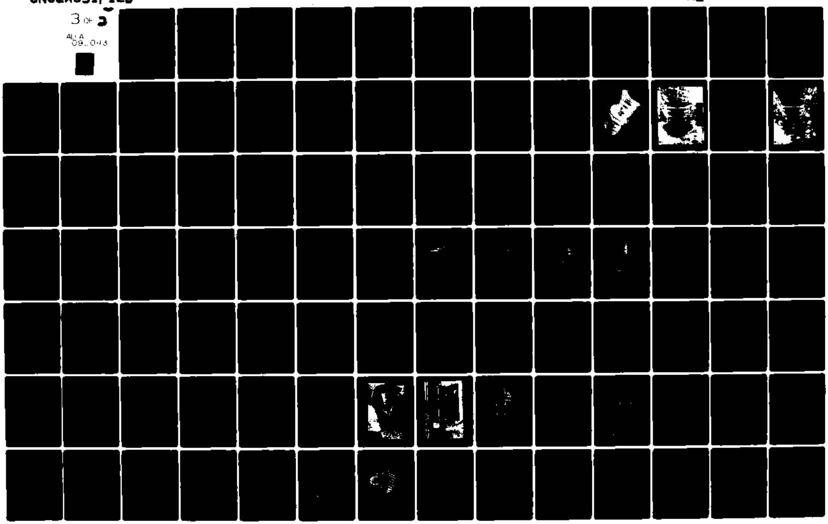


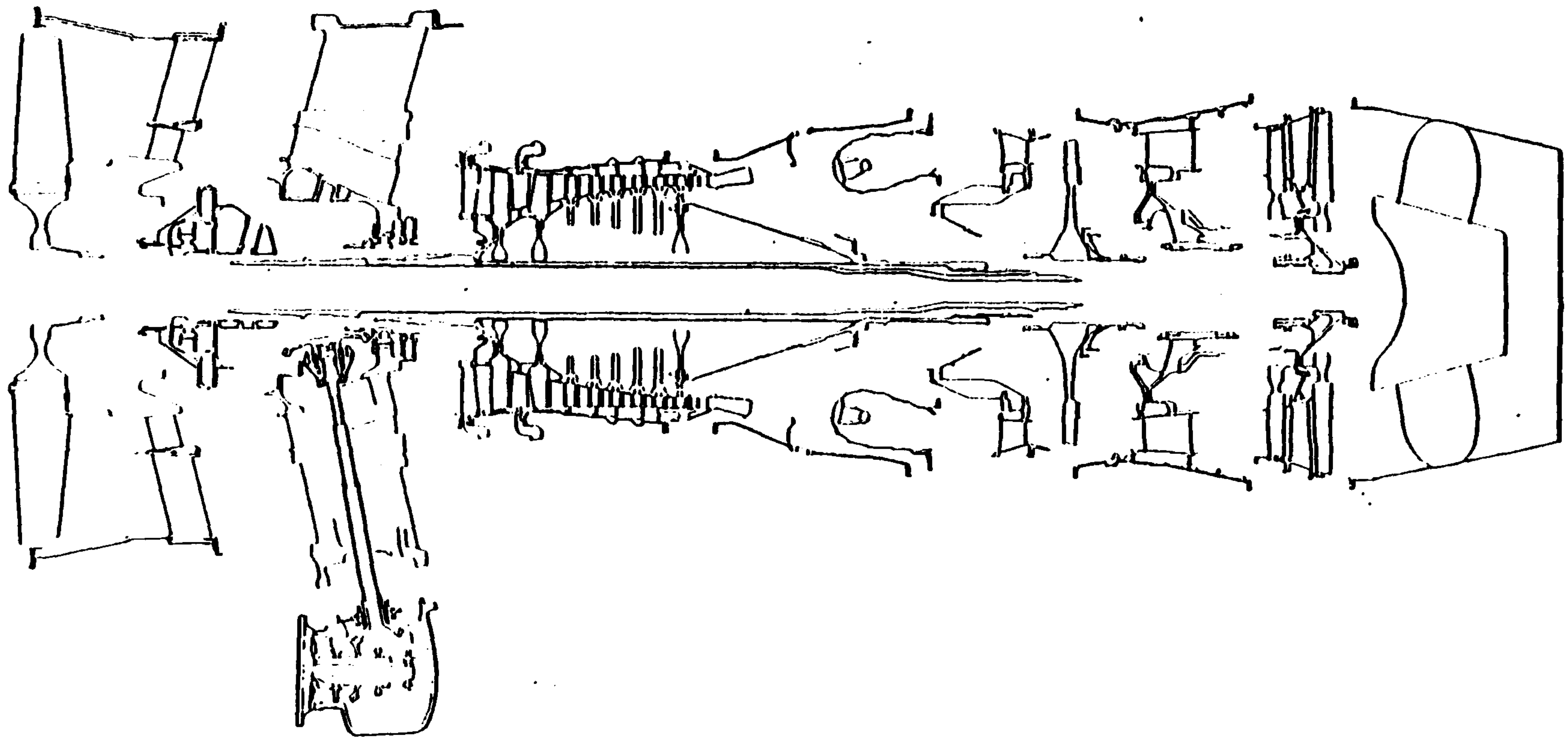


Fig. 22 RB 401 MODULAR ASSEMBLY

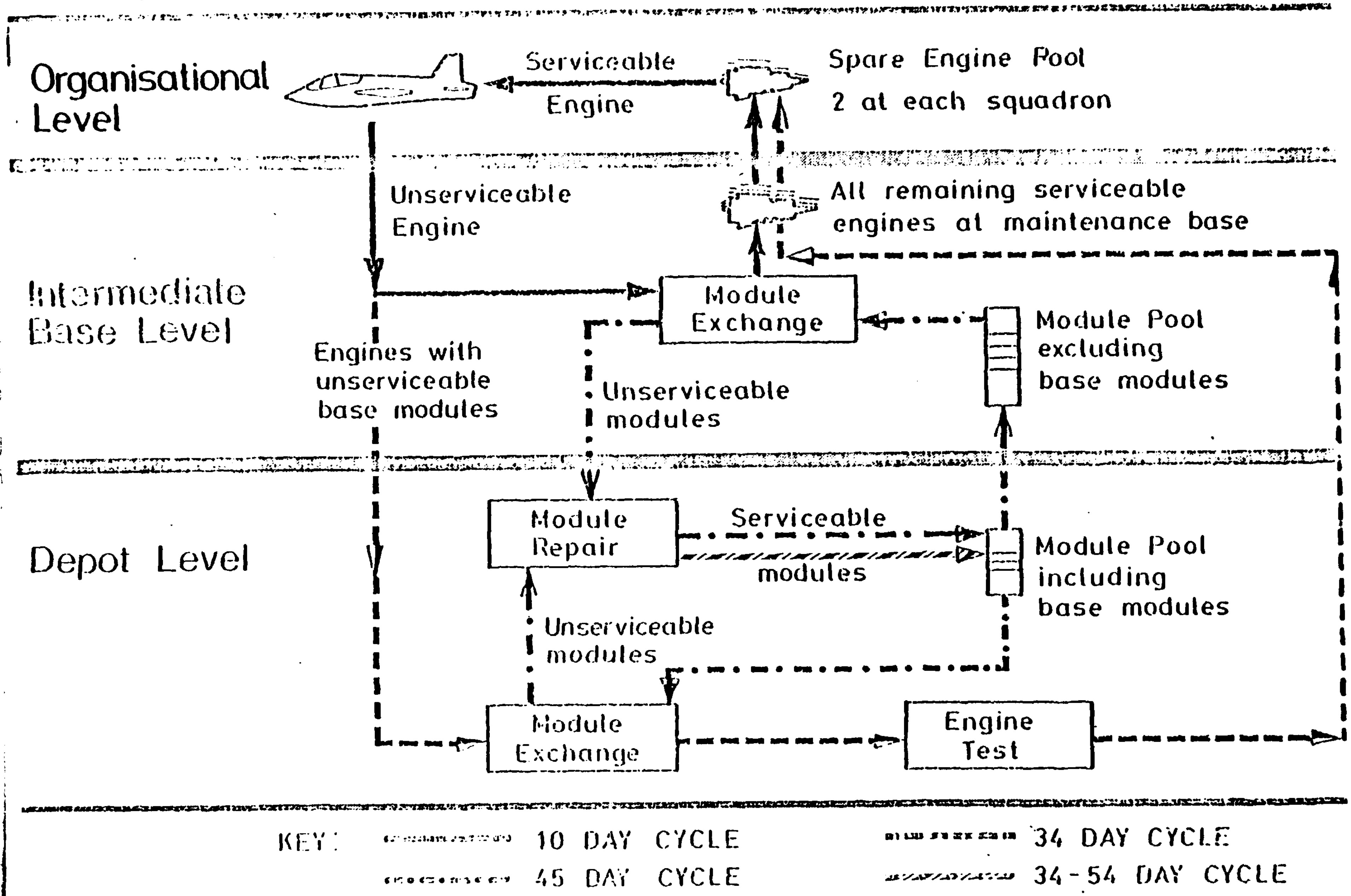


Fig. 23 Logistic Cycle. Partially Modular Engine

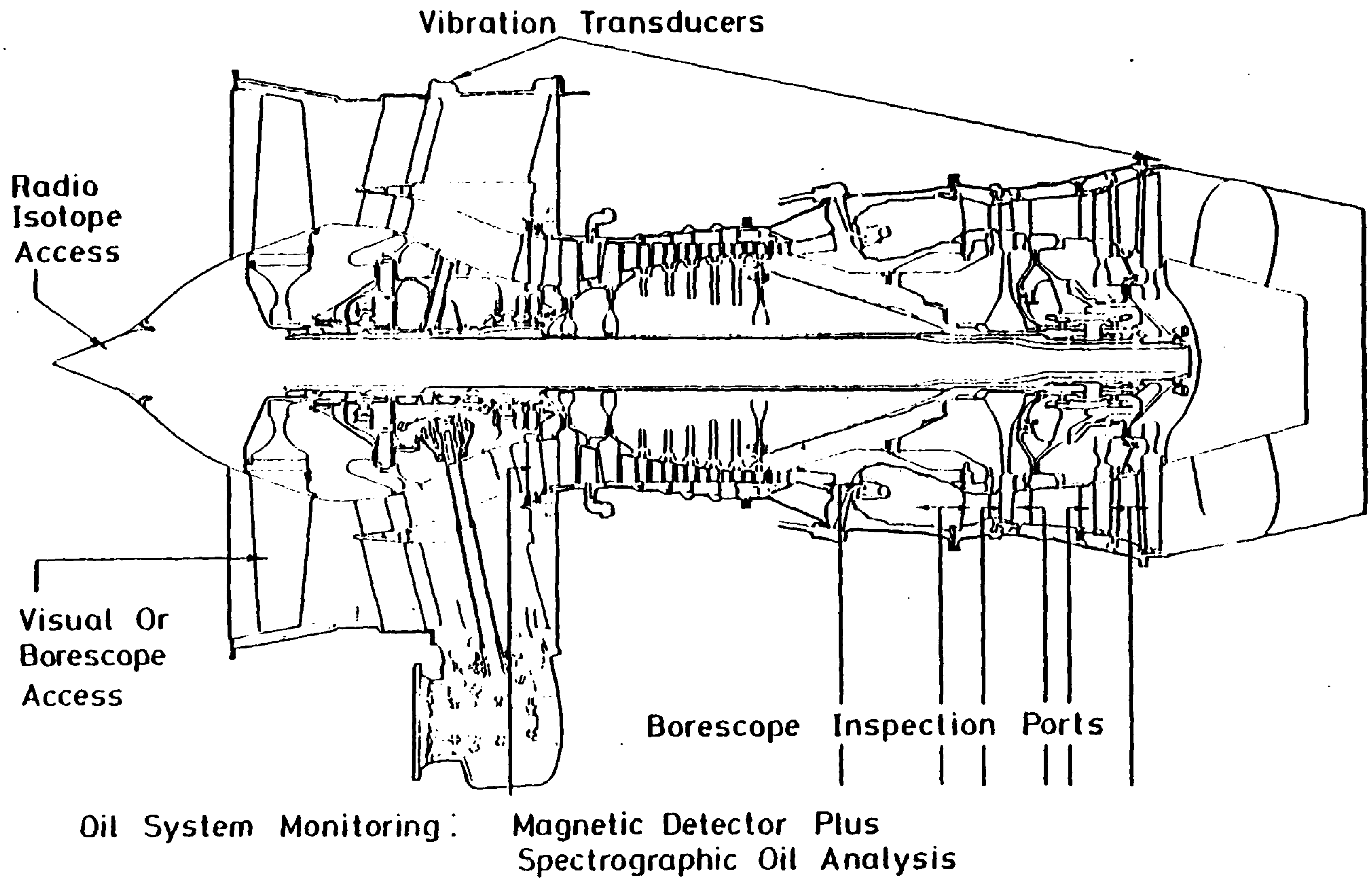
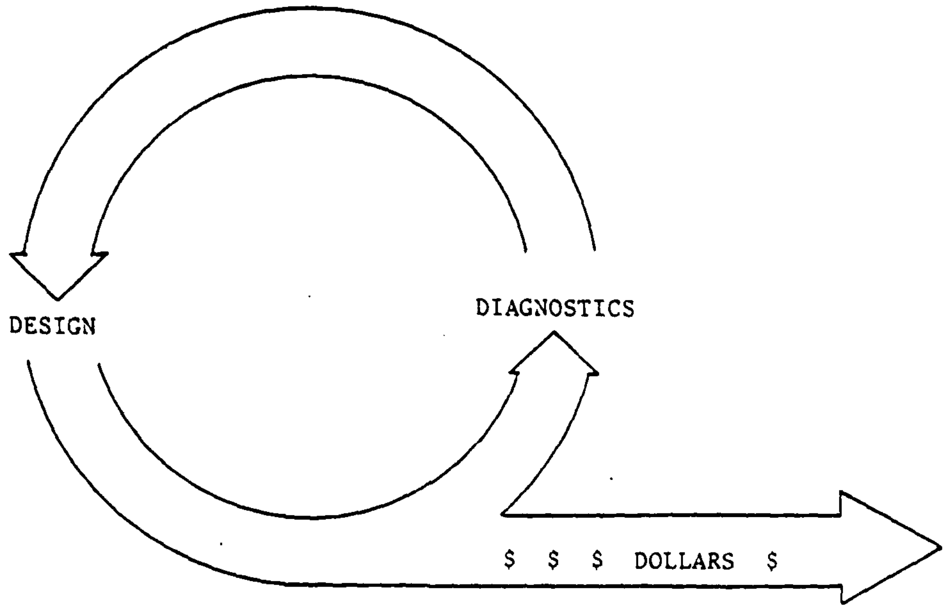


Fig. 24 Health Monitoring Facilities



Major Michael Shutak
Life Cycle Cost Office
Deputy for Propulsion Systems
Wright-Patterson AFB, Ohio

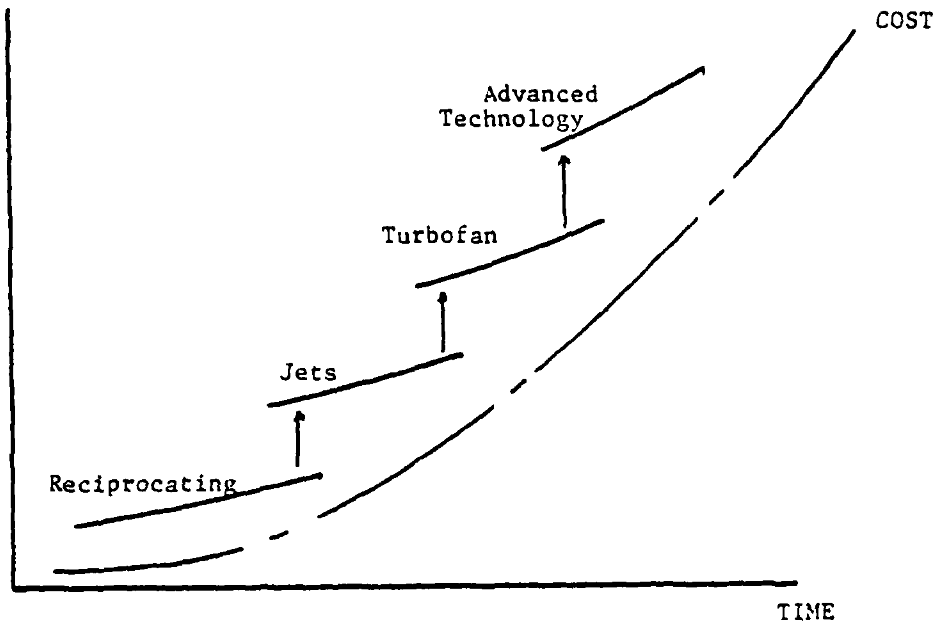
BACKGROUND

The history of propulsion system development has been characterized by:

- quantum jumps in technology
- proportionately increasing cost
- shifts in development curves

FIGURE 1

HISTORICAL PROPULSION SYSTEM DEVELOPMENT



This environment established a design-cost interaction characterized by:

- technology at any price
- design drives cost
- life cycle cost effects of design unknown or disregarded

In turn, costing methodology was influenced:

- the more advanced design was, relative to the past;
- the less related design was to systems for which experience data existed;
- and the greater the need was for parametric and analogous methodology able to predict costs from conceptual inputs.

Recently, however, the propulsion system development environment has exhibited indications of change:

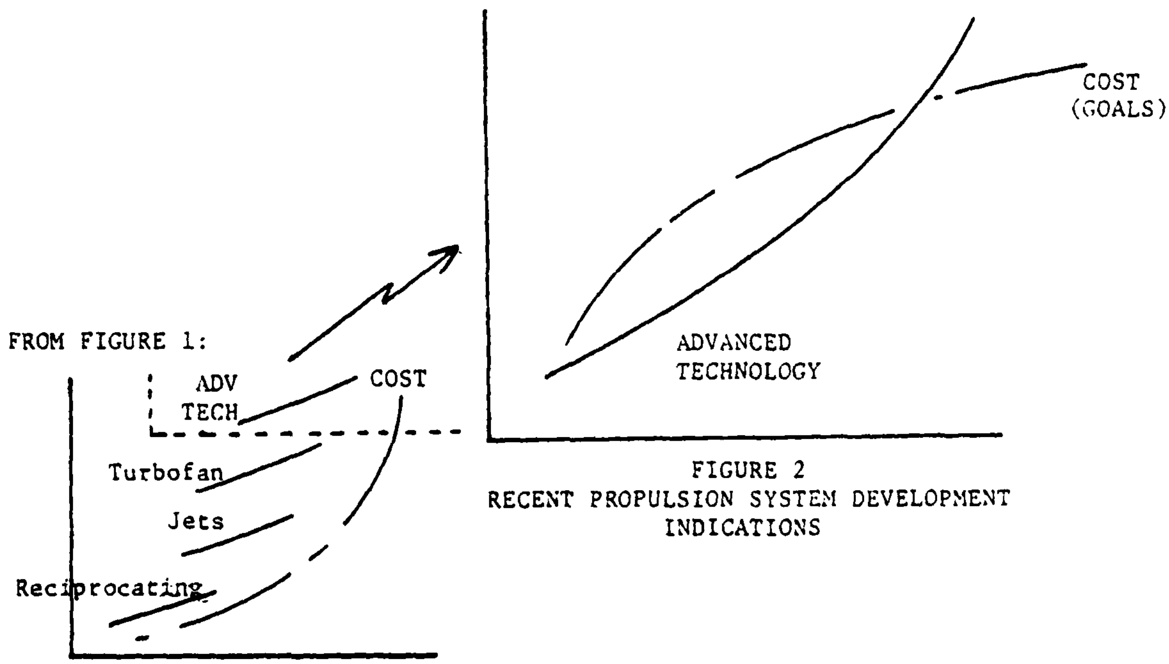


FIGURE 2
RECENT PROPULSION SYSTEM DEVELOPMENT
INDICATIONS

- designs are extrapolated/derived from the present

- emphasis is on improvement and extended capabilities versus shifts in technology; development is more movement along a curve than a shift to another level.

Costing methodology is again influenced:

- designs related more strongly to the past/present allow and to an extent require greater use of actuarial data

  -- present systems establish a technology and capability baseline

  -- methodology emphasis is parallel, focusing on cost baselines plus/minus cost changes.

- design objectives stress lower life cycle costs; cost methodology must measure more detailed elements, versus generalized quantification

- cost has become a more critical decision variable;

  -- the price of performance and technology is an issue

  -- development alternatives are being sold on the basis of life cycle cost improvements

Several examples typify these changes as they apply to propulsion system development:

- T56 engine derivatives for the C-130 family

- KC-135 re-engine options, including existing military and commercial engines

- multiple applications for the F100 engine

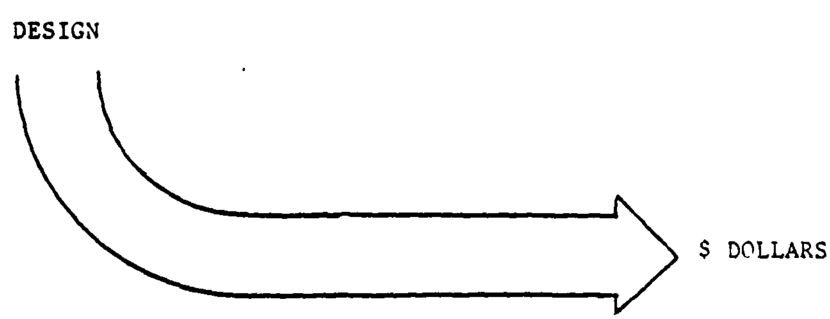
The examples have a common impact on the design-cost interaction: life cycle cost improvements are prime decision factors. In each case, design emphasis is at the sub-system level. Improved fuel economy with temperature and cooling changes is the T56 emphasis. The KC-135 re-engine options stress POL reductions and overall lower O&S costs. Use of proven engines at existing technology levels was expected to contribute to lower costs. The multiple applications for the F100 engine involve accessory differences with reliability and resultant cost advantages.

Beyond the hardware characteristics of recent propulsion system development effort, another factor has surfaced. The methods of operating and supporting propulsion systems can enhance or negate the cost reduction potentials of the hardware. Design has extended to maintenance concepts particularly on-condition maintenance.

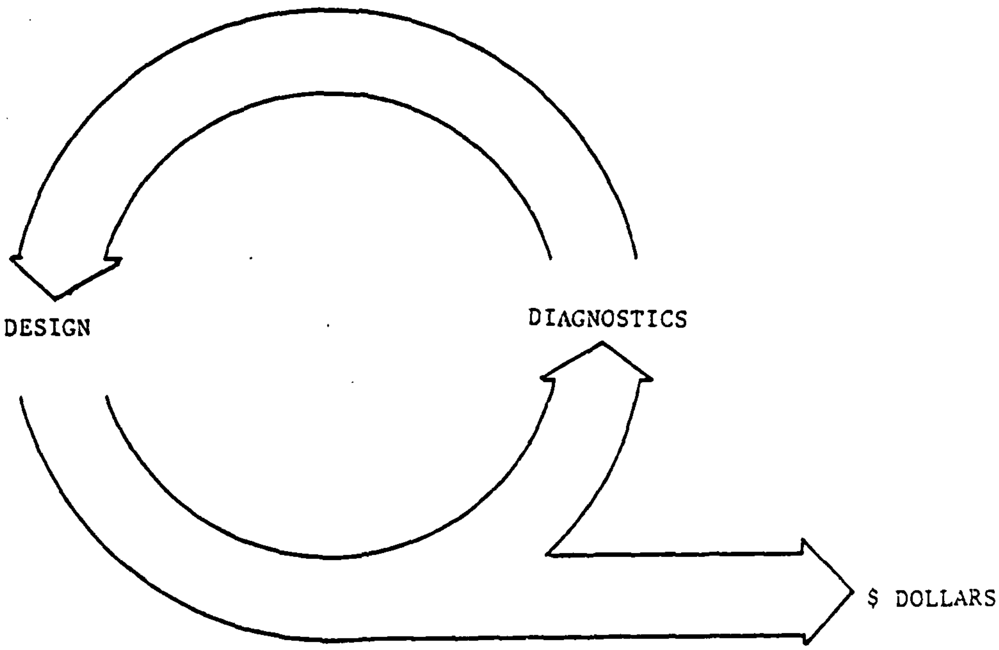
Propulsion system development has evolved towards designed-in cost improvements, both initially and throughout the life cycle. One design area receiving significant emphasis is engine diagnostic systems.

DESIGN, DIAGNOSTICS, AND DOLLARS

The design-dollar interface was established with the background discussion of the propulsion system development environment:



The addition of diagnostics completes the loop and defines the main thrust of this paper as the design-diagnostics interface and related impacts on life cycle costs/methodology:



Three sets of potential benefits are envisioned, in each of the three phases of the life cycle: RDT&E, acquisition, and operating/support (O&S). In each phase, diagnostics systems have the potential to positively interface with design.

RDT&E

The major design effort during this period can benefit from diagnostics systems in two ways: One, by concentrating design effort upon the results of lessons learned from previous systems;

and two, by designing to a defined maintenance concept from the earliest possible point in the life cycle. Both depend upon the accurate data recording capabilities of diagnostic systems.

ACQUISITION

Design benefits expected during the acquisition phase are in the engineering change and component improvement activities. The ability to focus design effort on specific causes of problem categories depends upon the improved troubleshooting and data collection accuracy expected from diagnostics systems.

O&S

The O&S phase provides the experience for measuring the effectiveness of design effort; again, the measurement and recording capabilities of diagnostic systems are the key assets.

The major contribution of diagnostics systems to design can be summarized as a continuous feedback loop, providing accurate data for design effort.

Beyond design effort, diagnostics systems are both typical examples of the present trend in propulsion systems development and a solution to the life cycle costing problems created by these trends. The majority of the potential benefits of diagnostics systems, like many of the current engine related improvements, occurs during the O&S phase. The ability to measure baseline O&S data required to evaluate such projects is enhanced by the data recording/tracking attributes of diagnostics systems.

Two proposed engine diagnostics systems were selected as examples for the design-diagnostics-dollar interface:

- Turbine Engine Monitoring System (TEMS) for the TF34-GE-100 engine
- Engine Diagnostic System (EDS) for the F100-PW-100 engine

Both systems exhibit similar categories of benefits: reduced POL/parts consumption; reduced maintenance man hours; secondary damage avoidance; and improved attrition experience. Benefits depend upon the degree of integration of the diagnostics system into the maintenance concept. Superimposing diagnostics without revising maintenance policies only creates an additional layer of cost without realizing full benefit potential.

Full benefit potential is substantial: for TEMS, up to $400 million (FY78 $) over the A-10 life cycle; for EDS, up to $850 million (FY77 $). Savings are driven by improved diagnostic ability leading to fewer engine removals and reduced engine operating hours for diagnosis, trim, and test. The ability to detect events before resultant damage occurs, e.g. over-temperature incidents leading to blade failure, generates significant benefits in secondary damage and attrition reductions.

CONCLUSION

Engine diagnostics systems have the potential to close the loop between design effort and operating effects while substantially reducing O&S costs. The improved, more detailed data base possible

with diagnostics also enhances our ability to measure and predict the life cycle cost impacts of propulsion system development options.

PRECISION CAST TITANIUM COMPRESSOR CASINGS FOR THE T700 ENGINE

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INTRODUCTION

The T700-GE-700 engine was developed with compressor casings which were fabricated from titanium forgings machined all over - inside, outside and both ends. The finished casing is seen in Figure 1. The presence of the longitudinal flanges on this part preclude turning the outer surfaces, instead demanding milling, a relatively slow and therefore costly means of metal removal. Figure 2 shows the forging from which the finished part was made. External features including brackets, bleed ducts, etc., were fabricated separately and attached by welding. It appeared that substantial savings would accrue if precision casting could be applied to the fabrication of this casing, casting the outside contours to finish dimension, and that at least some of the welded-on externals could probably be cast integral. An estimate of potential savings, if the casting

processes were applied, indicated about $658 per engine in 1976 dollars, and a contract for the necessary MM&T effort was awarded to the engine contractor, General Electric. The effort was funded by AVRADCOM through ATL. Throughout the course of the process development, General Electric was strongly supported by their casting vendor, Precision Castparts Corporation of Portland, Oregon. The results are due to their combined efforts.

CASTING PROCESS DEVELOPMENT

In view of the configuration, it was decided to apply centrifugal casting using the same alloy, Ti6AL4V, trying both shell molding and permanent mold techniques. Early results led to concentration on the shell molding process. This course was selected as being the simpler development problem and as requiring less costly production tooling which would be more flexible to the introduction of design changes as well as variations in processing which might be found desirable. Figure 3 shows the casting as developed. Although in some locations on the finished casing it was found possible to take advantage of the casting process by eliminating excess metal which the combined forge and machine methods had left, the net weight results have been 8.8 lbs as forged and machined compared with 9.3 lbs as cast and finished. The weight increase is associated primarily with required casting tolerances. All of the external features were previously welded on the machined forging. As cast, all except the elbows are integral.

These castings do not require hot isostatic pressing (HIP).

Approximately 35 castings have been poured, of which 15 used pilot production metal pattern dies. The others used temporary, epoxy dies of simplified configuration. The casting tooling was developed gradually in the solution of successive problems. Although presently satisfactory, the probability exists that a sustained production effort will encounter circumstances rendering desirable some modification of either tooling or procedure, or both.

Due to its reactivity at high temperatures and to its high melting point, approaching 3000°F, titanium is melted and cast in a vacuum arc melting furnace and requires the use of a water-cooled copper crucible in which the melting ingot first provides a titanium lining or skull. This insures that the titanium poured into the mold does not contact the crucible wall directly, but also results in virtually a zero superheat in the charge entering the mold. The entering titanium is therefore subject to freezing very rapidly at the mold interface once contact occurs. Properties of the mold ceramics limit the degree of preheat and the mold temperatures used here ranged from 1550°F initially to 1800°F on all later castings.

Centrifugal casting is used. Centrifuge rotor speed depends on the configuration to be cast and was selected empirically for this configuration. Speeds from 200 to 500 rpm were tried; 350 rpm appears to be the optimum in this case. Casing OD is about 11 inches at the rear flange. Length is about 10½ inches. Castings are annealed at 1300°F,

and about .025 is chemically milled off on all surfaces, removing any oxygen rich alpha case and all other surface contamination. Radiographic inspection is performed. It is to be noted that, while the case forgings weigh 65 lbs, the weight of the castings as removed from the mold, untrimmed, is only 35 lbs.

DEVELOPMENT PROBLEMS

Principal problems encountered in the development include:

1. Shrinkage, particularly near the Y joint, where the rear flange joins the main body of the case.

2. Surface roughness. Since the design wall thickness permits a minimum of .055 in finished thickness in some areas, this can be structurally critical aside from cosmetic considerations.

3. Diametral shrink and distortion of the mid section.

4. Integration of bleed elbows.

A further explanation of these problems and their solutions follows.

Shrinkage: Early castings were poured with the rear flange solid between the inside of the cone and extension of the main body of the casing. Finished thickness of the flange web is .200. The tooling

was modified to include an annular ring in this area, producing a near net shape in this area with flange web thickness of .250 as cast and chem milled, reducing the mass of metal involved. Insulation between mold and turntable was increased. The shrinkage was eliminated. Shrinkage was encountered in the rear flange rim. Improving the feed to this area by providing direct feeds to the flange through radial "spokes" subsequently machined off, eliminated this problem.

<u>Surface Finish</u>: Until well into the program all castings were poured in a mold effectively consisting of an outer wall only, the molten titanium being dumped in at the top or forward end of the mold in the space of a few seconds. Striking the bottom plate of the mold it was centrifuged to the side walls where it climbed the slightly conical surface. However, considerable spattering occurred, with droplets impinging on the mold surface and freezing in advance of coverage by the main flow. With the lack of superheat in the molten titanium the main flow could neither remelt the droplets nor bond well to them. As a consequence, pits were produced in the cast surface. Since the finished wall thickness can go as low as .055 in certain areas, even small pits can be structurally critical as well as cosmetically undesirable. Some degree of improvement was achieved by adding a contoured boss to the bottom of the mold on the centerline; this served to divert the spatter and tended to confine it to the bottom region of the mold which was covered more quickly. Complete cure required the introduction of an inner wall to the mold, which served as a spatter shield, and of a central sprue with gates at the aft or bottom end. Figure 4 shows the mold arrangement. This

was also involved with the third problem.

Diametral Shrinkage and Distortion: With the introduction of the pilot production tooling, it was necessary to completely dimensionally inspect the castings. It was found that the castings were subject to diametral shrinkage through their mid sections and that the degree of shrinkage varied significantly among castings. The first step in correcting the error was to introduce the inner wall already described to the mold, thus better controlling the cast wall thickness and reducing the variables. This was successful in that variations among castings were markedly reduced. A clear pattern emerged. The apparent shrinkage included deviation in roundness as well as in circumferential length. The unequal stiffness across the plane of the axial flanges and across the axial plane normal to the flange plane was resulting in the flanges bowing out and the 90° position bowing in. Much of this was found to be present in the wax patterns. This condition was corrected by sizing and final shaping the wax patterns on a conical mandrel before commencing buildup of the mold. This appears to have corrected the situation, although it may subsequently be found desirable to fixture the castings during the anneal cycle.

External Features: As previously stated, with forged and machined cases all external features were welded on. It was established early in the program that, with the exception of the air bleed elbows, all external features could be cast integral without causing problems. Provisions for them were incorporated in the pilot production pattern die. Estimates

indicated that if satisfactory elbows could be cast integral, an additional unit savings of $150 per engine should accrue. These savings would result not only from the elimination of all routine welding operations directly, but from the elimination of associated preparatory machining, cleaning, post-weld annealing and radiographic inspection, not to mention separate fabrication of the elbows.

Early trials had indicated that the principal problems involved would be establishing the minimum castable wall and avoiding shrinkage in elbow flanges. The contract was amended to include the effort judged necessary to include integrally cast elbows. Since timing was critical, this work was conducted so as not to interfere with the original contract schedule. Modification of pilot production dies, prematurely committing them to the inclusion of the elbows, was not allowed. Elbow patterns were formed separately and were wax welded to the main pattern.

Several castings were poured. A sample is shown in Figure 5. It was not found feasible to cast walls less than .170 thick, reduced to .120 by the overall chem milling. Compared with the fabricated elbow of .035, this resulted in a .6 lb weight penalty. Preferential chem milling was found to be unsatisfactory. Special gating to eliminate shrinkage in the duct flanges failed to achieve its objective. It became apparent that, although these problems probably could be solved eventually, the added complexity would adversely affect the yield of the process and would, in any case, materially raise the cost of the castings, effectively cancelling the estimated savings. Therefore, the effort to integrate the elbows was abandoned. Casting production casing per Figure 3 is planned, fabricating and welding on the bleed elbows.

Figure 6 shows diagramatically the areas where casting results in improved material utilization and indicates weights involved.

Figure 7 provides comparative figures for the costs incurred in the manufacture of both forged and cast casings.

With casting, although material utilization is much better, the delivered casting cost slightly more than the forging. The hardware identified on Figure 7 covers the items which are or were fabricated separately and welded on. Some savings are due to reduction in hardware. The bulk of the savings, however, come from elimination of 31 manhours machining operations on the cast exterior. A net savings of $658 per casing has been realized.

MATERIALS PROPERTY TESTS

Tensile, high and low cycle fatigue, creep and stress rupture and crack growth data were obtained at temperatures between room temperature and 800°F using specimens cut from the casting. The tests were executed by Metcut Research of Cincinnatti, Ohio. The data from these tests is seen in Figures 8 - 17. As anticipated, materials test data results were somewhat lower than forging properties, but were found to be adequate for the application.

SUMMARIZING RESULTS

Substituting precison casting for forgings has permitted improvement in material utilization from a 65 lb forging to a 35 lb casting as poured. HIP is not required. As delivered by the foundry, casings weigh 30 lb. Machining time and complexity are significantly reduced with an overall unit savings of $658. Except for bleed elbows, all external features are cast integral. The sole undesirable factor resulting is the weight increase of .5 lbs or 5.7 percent. Cast casings are due for engine test during the present month (May). It is fully anticipated that this test will demonstrate the suitability of casings thus manufactured for use in Army T700-GE-700 engines.

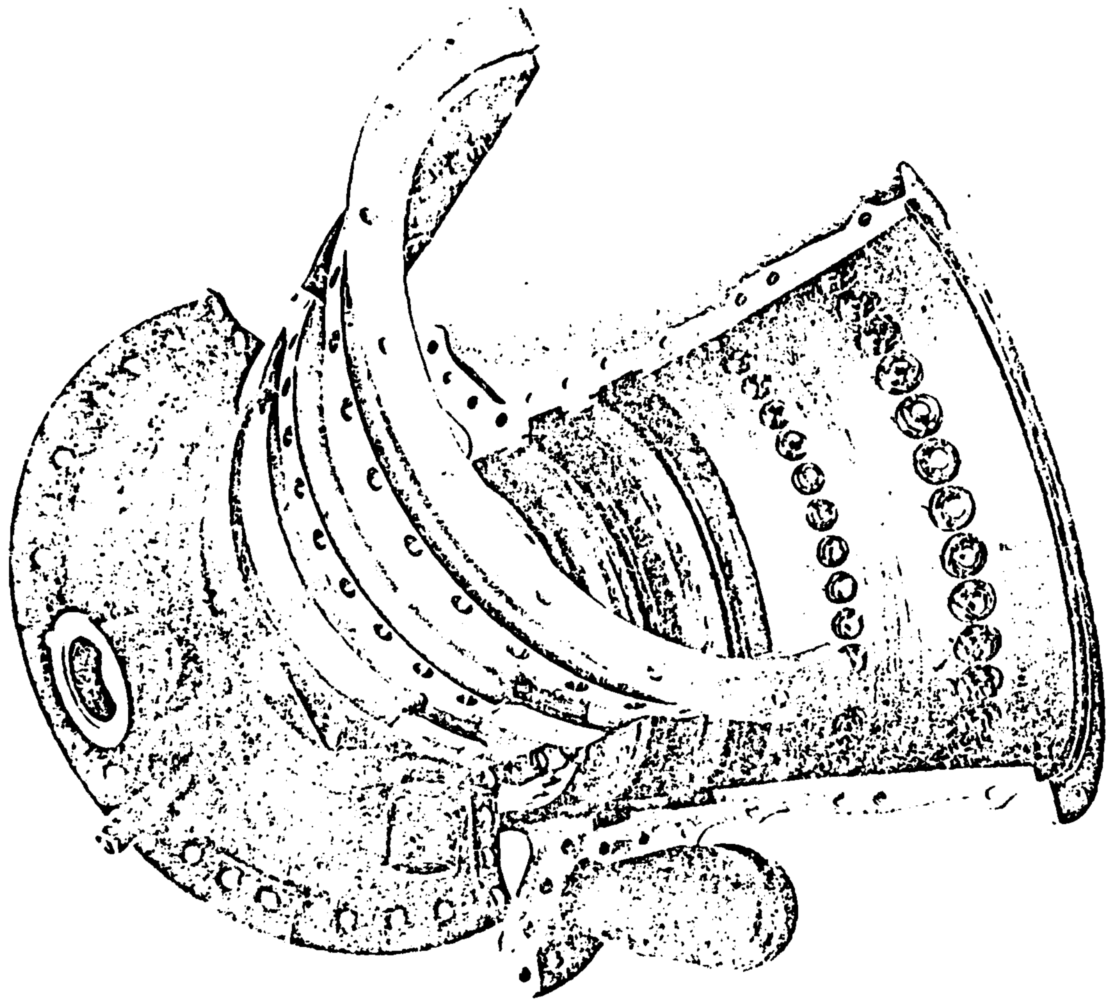


Figure 1

FINISHED COMPRESSOR CASING - FORGED

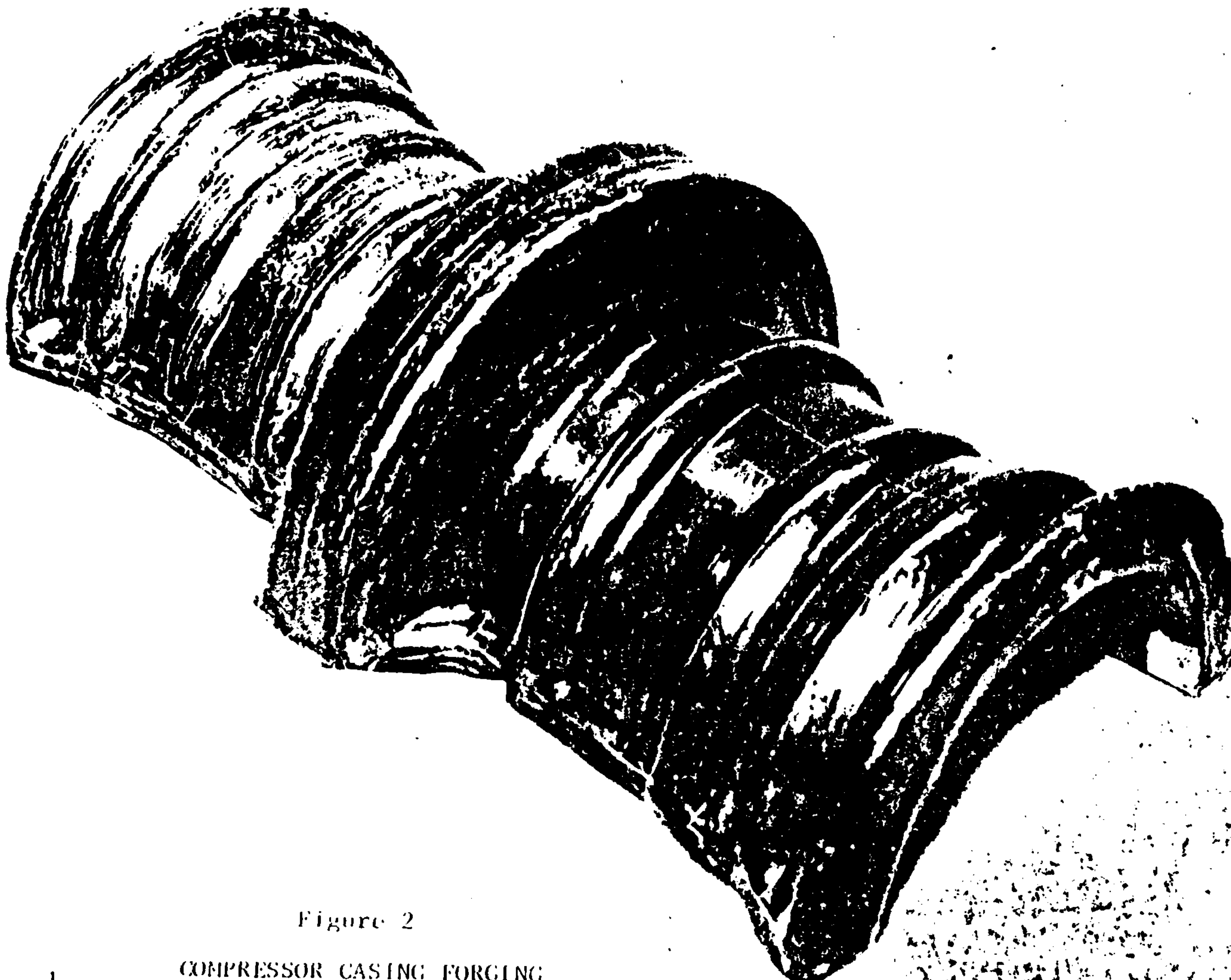


Figure 2

COMPRESSOR CASING FORGING

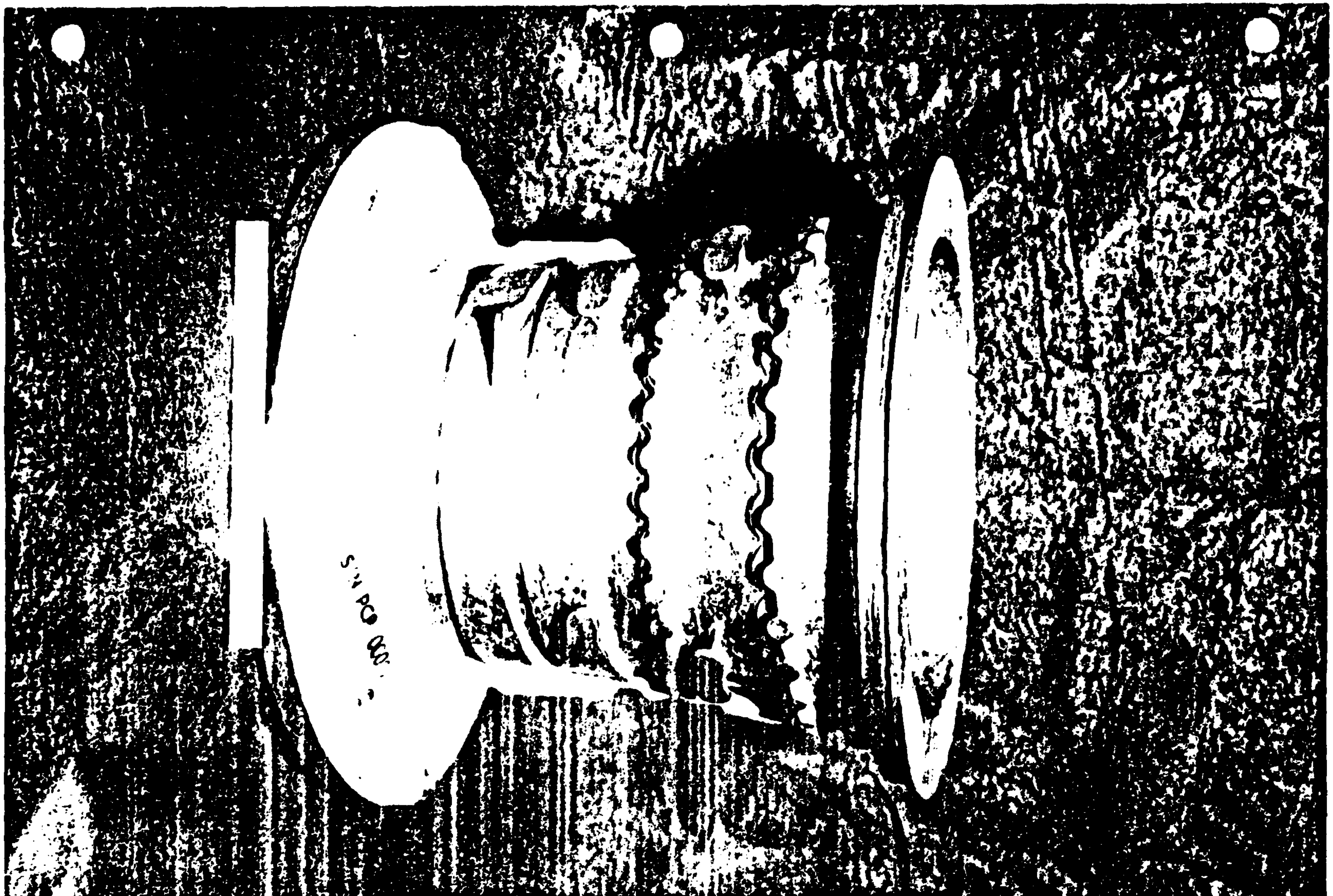
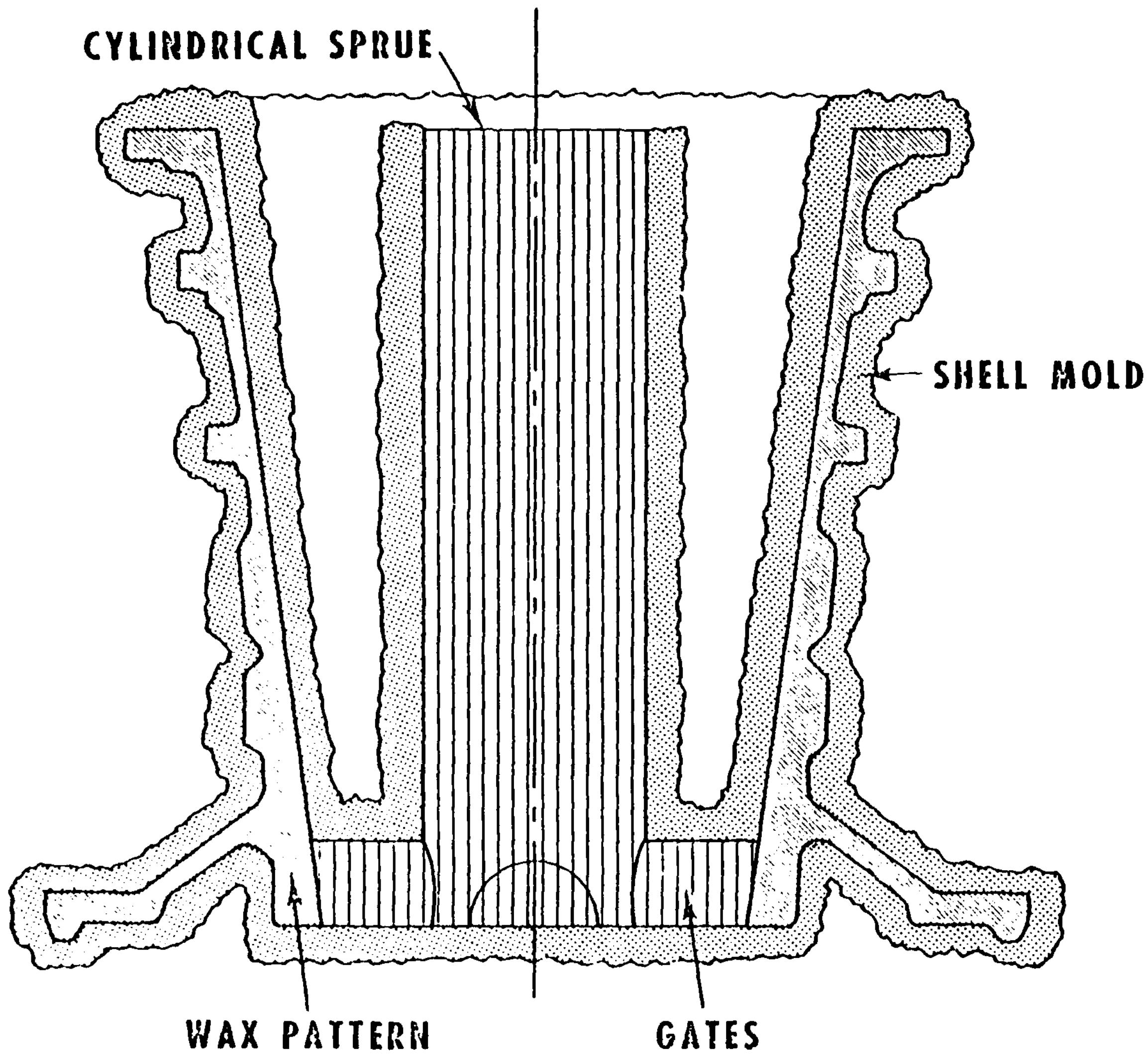


Figure 3

COMPRESSOR CASING CASTING

Figure

MOLD CONFIGURATION



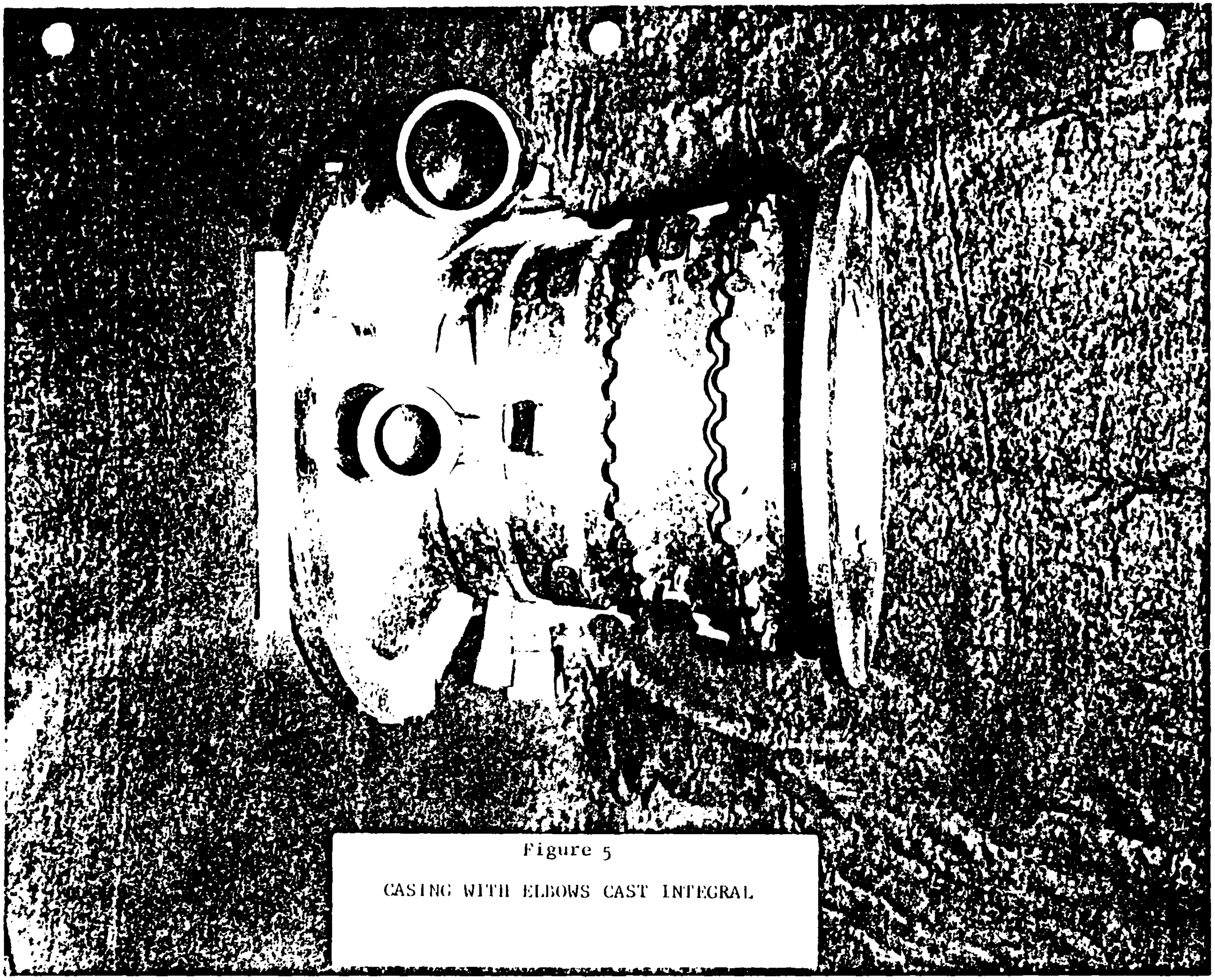


Figure 5

CASING WITH ELBOWS CAST INTEGRAL

T700 COMPRESSOR CASING
CASTING VS FORGING

	FORGED	CAST
MATERIAL WEIGHT	65 LBS	35 LBS
FINISH WEIGHT	8.8 LBS	9.3 LBS

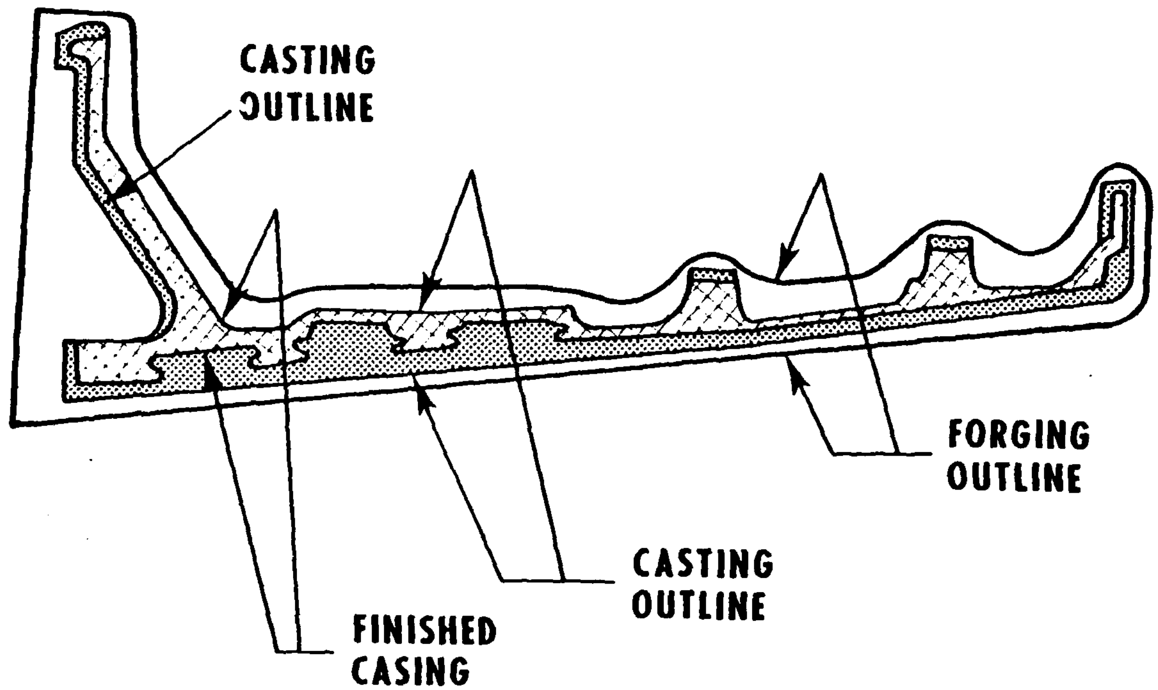


Fig. 6 - LESS MATERIAL & MACHINING

Fig.7 FORGING vs CASTING COST COMPARISON
(1976 DOLLARS)

FORGED CASING		CAST CASING	
FORGING	\$925	CASTING	\$1,050
HARDWARE	633	HARDWARE	505
	\$1,558		\$1,555
LABOR	81.6 HRS.		51.0 HRS.
	\$1,745		\$1,090
TOTAL	\$3,303		\$2,645
			$\triangle$ = \$658

Figure 8. UTS COMPARISON OF FORGING AND CENTRIFUGALLY CAST Ti-6Al-4V

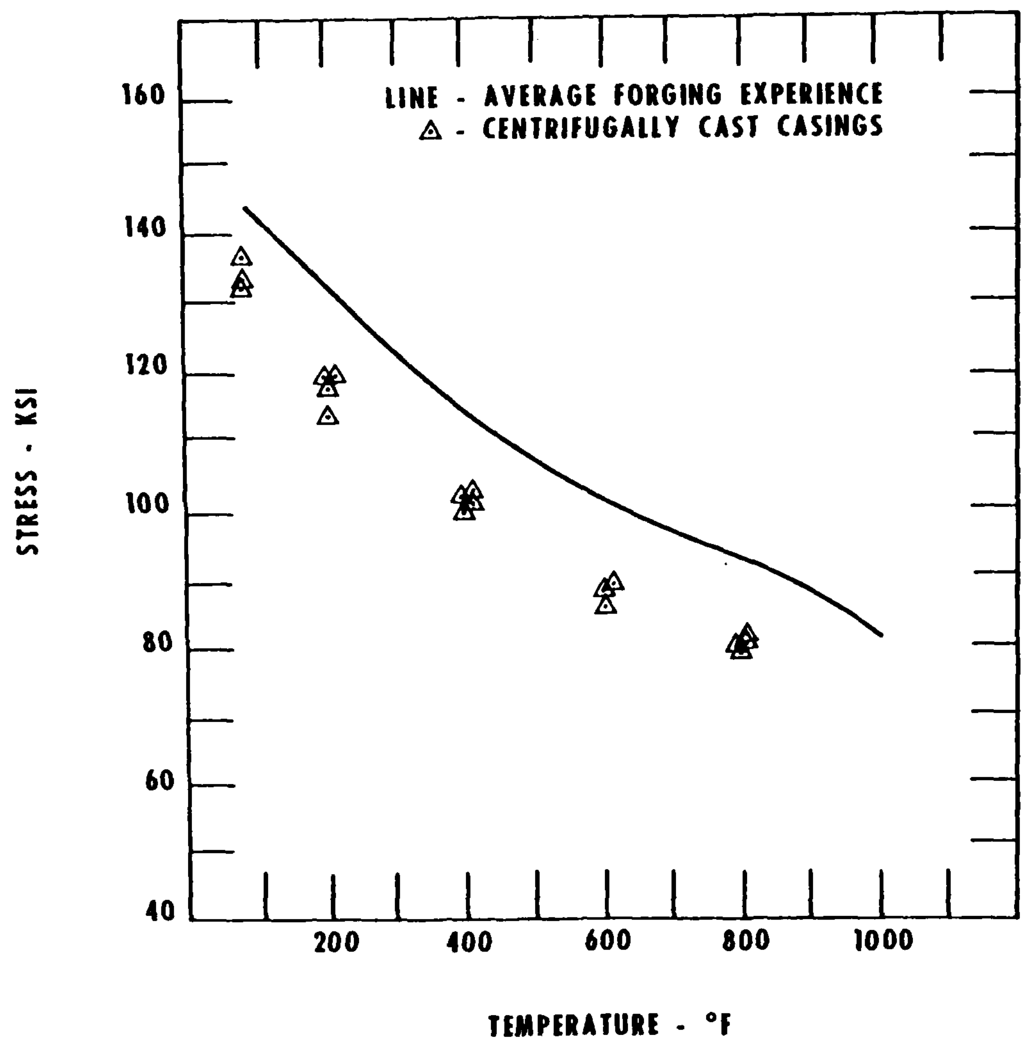


Figure 9. 0.2 PERCENT YIELD STRENGTH COMPARISON OF FORGING AND CENTRIFUGALLY CAST Ti-6Al-4V

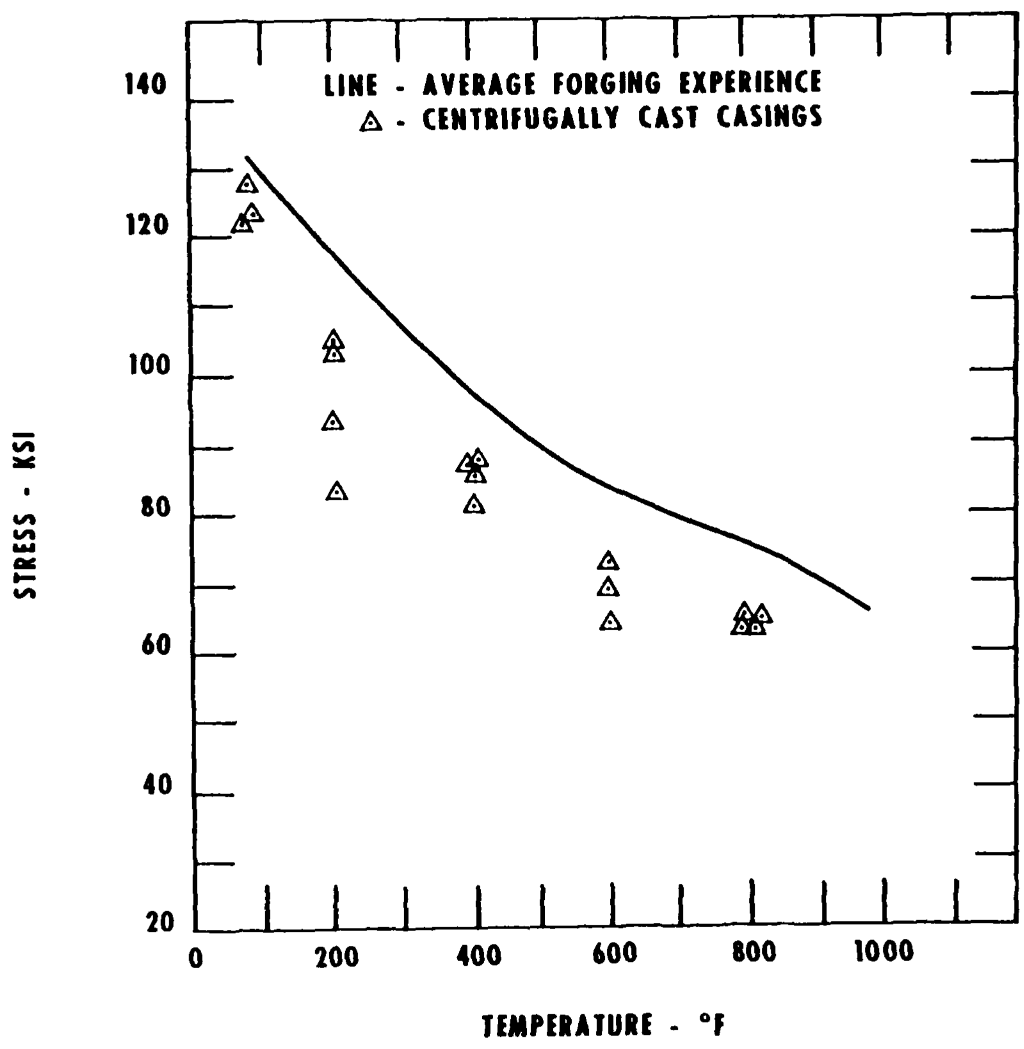


Figure 10. TENSILE ELONGATION COMPARISON OF FORGING AND CENTRIFUGALLY CAST Ti-6Al-4V

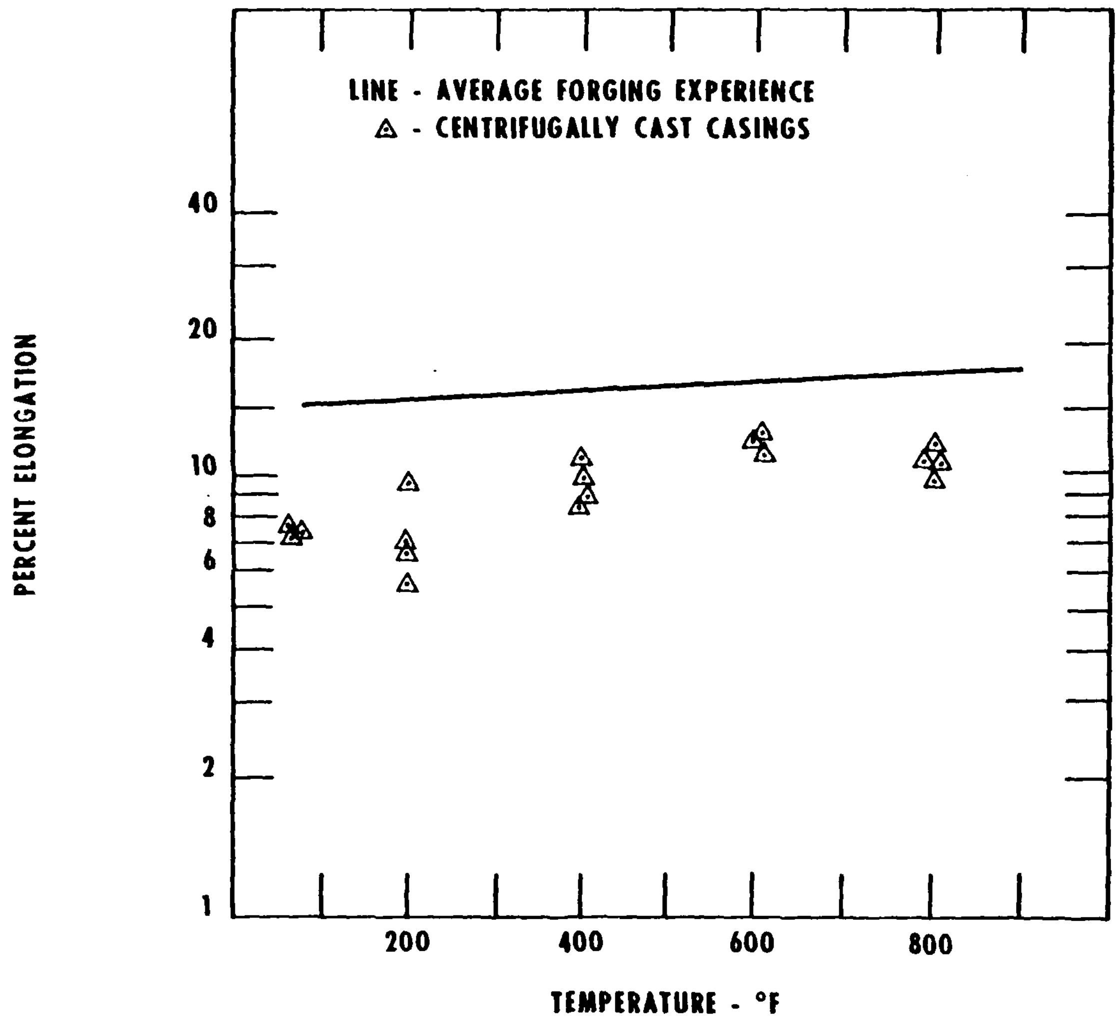


Figure 11. TENSILE REDUCTION OF AREA COMPARISON OF FORGING AND CENTRIFUGALLY CAST Ti-6Al-4V

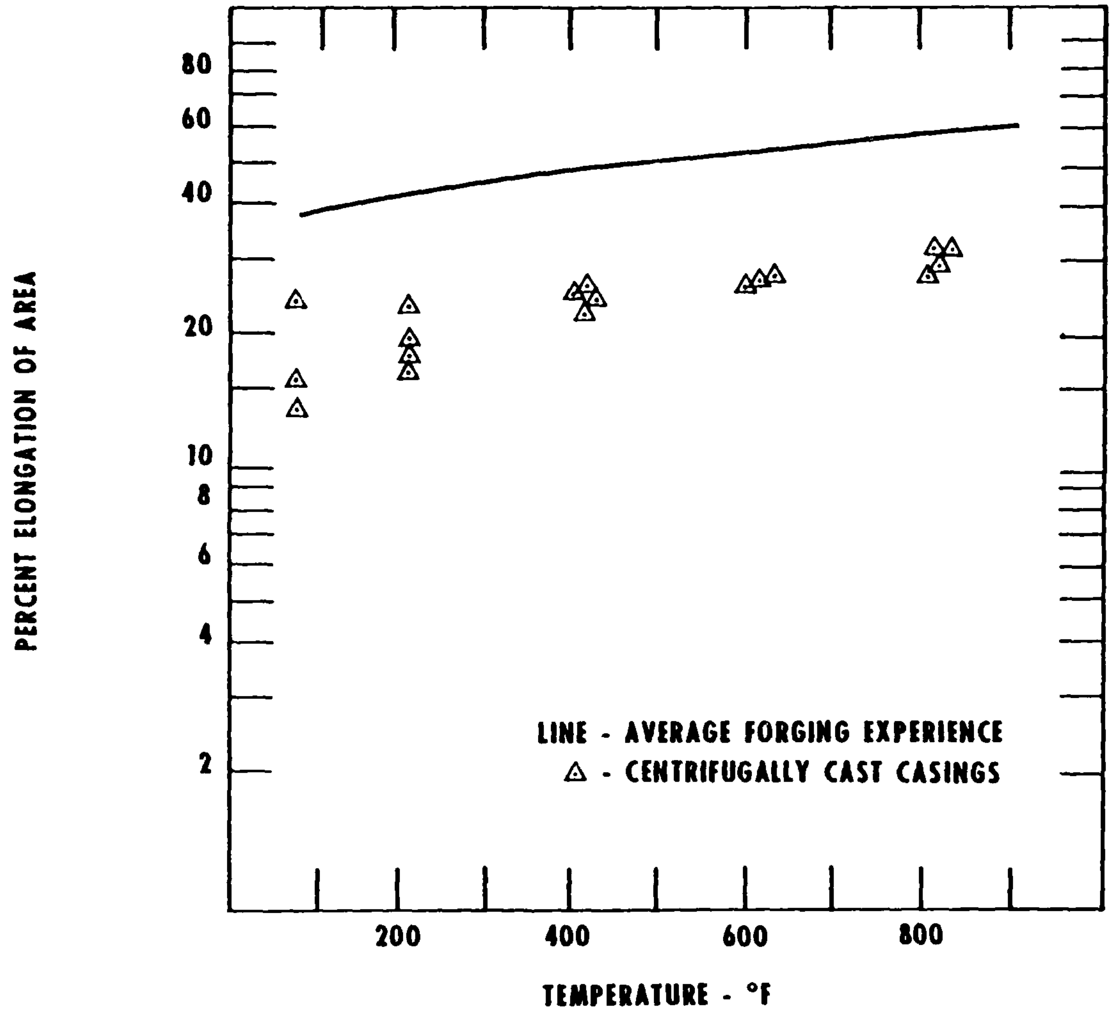


Figure 12. HCF COMPARISON OF FORGING AND CENTRIFUGALLY CAST Ti-6Al-4V - RM TEMP

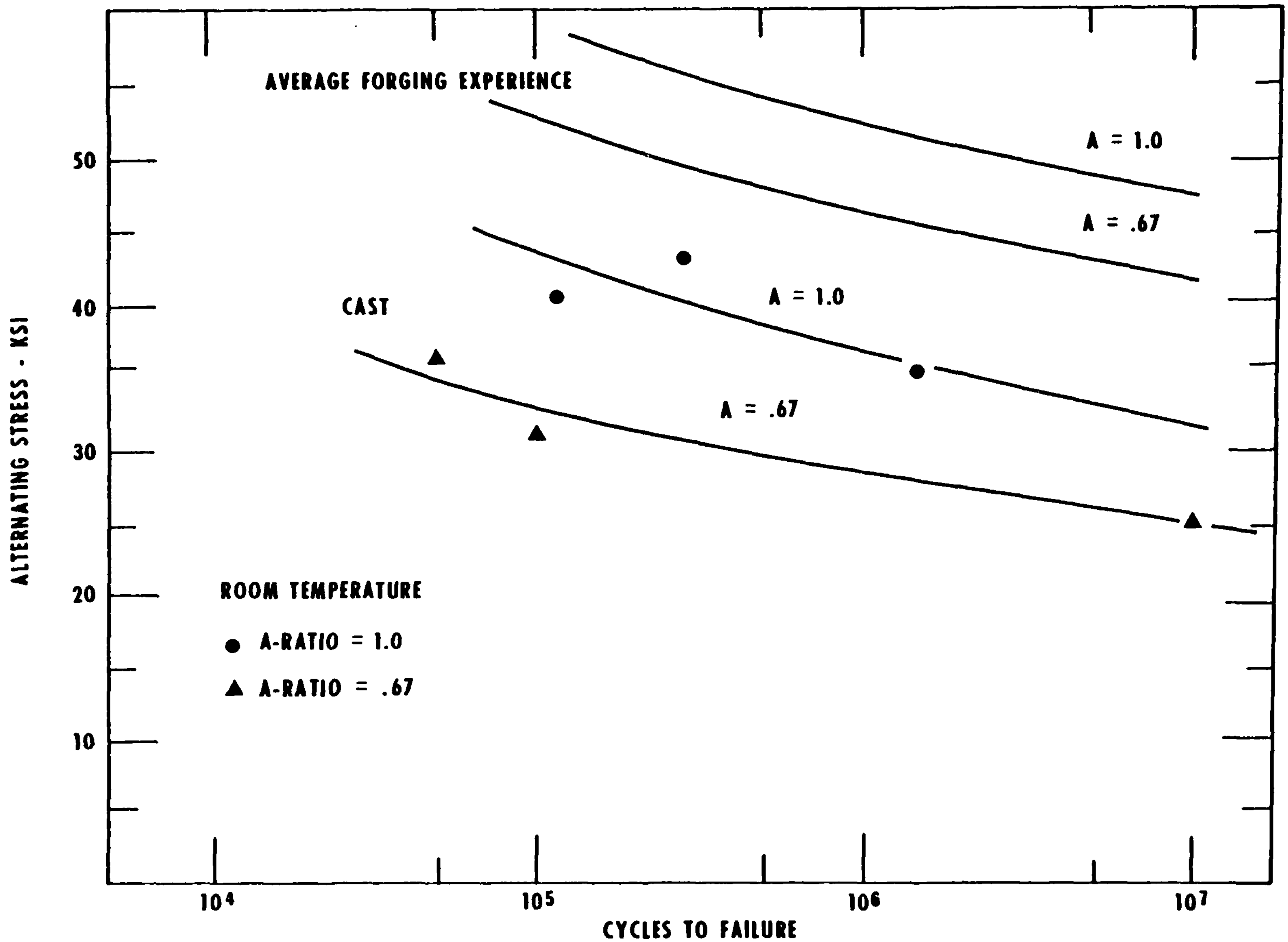


Figure 13. HCF COMPARISON OF FORGING AND CENTRIFUGALLY CAST Ti-6Al-4V - 600°

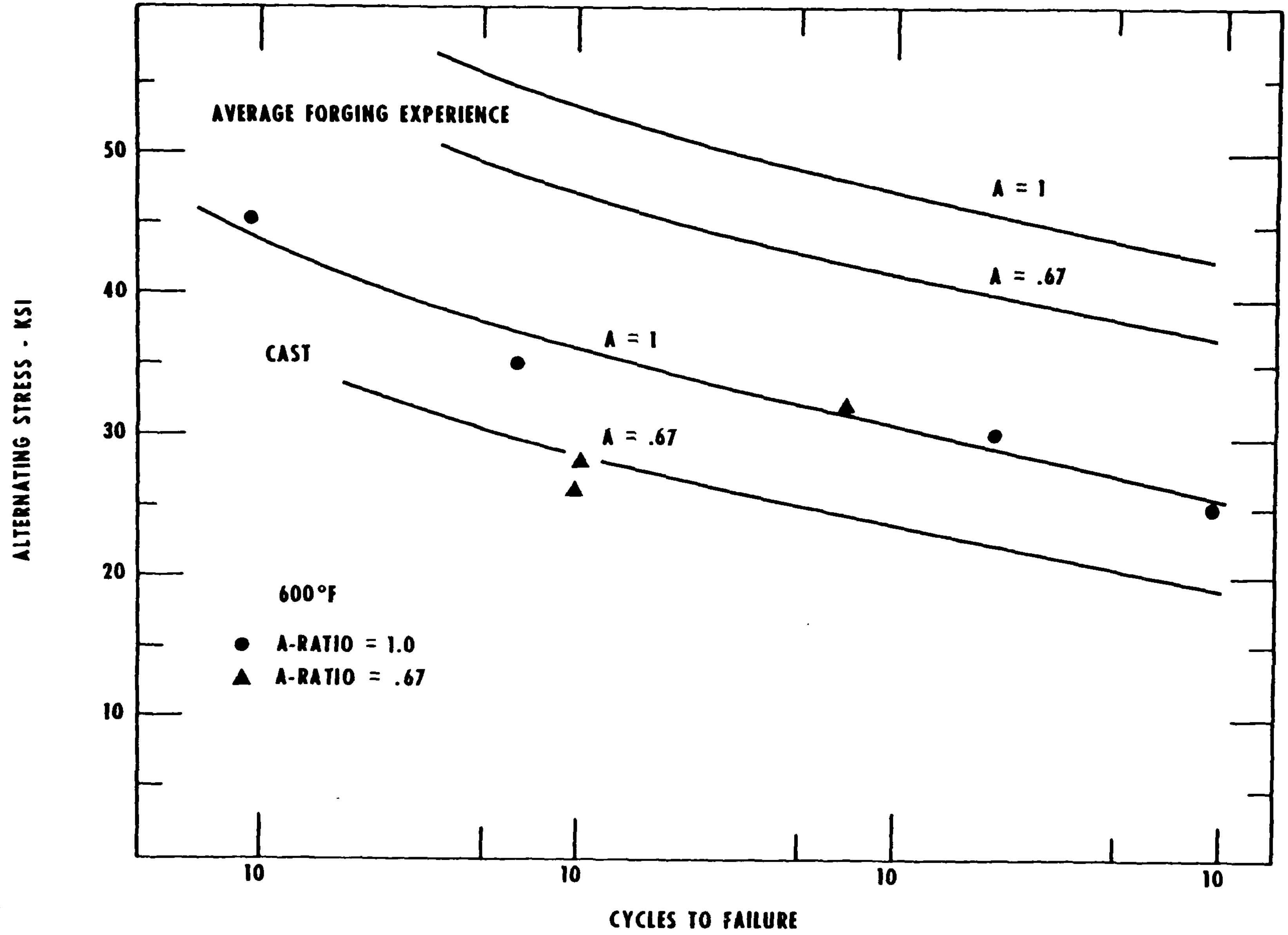


Figure 14. LOW CYCLE FATIGUE STRENGTH COMPARISON OF FORGING AND CENTRIFUGALLY CAST Ti-6Al-4V

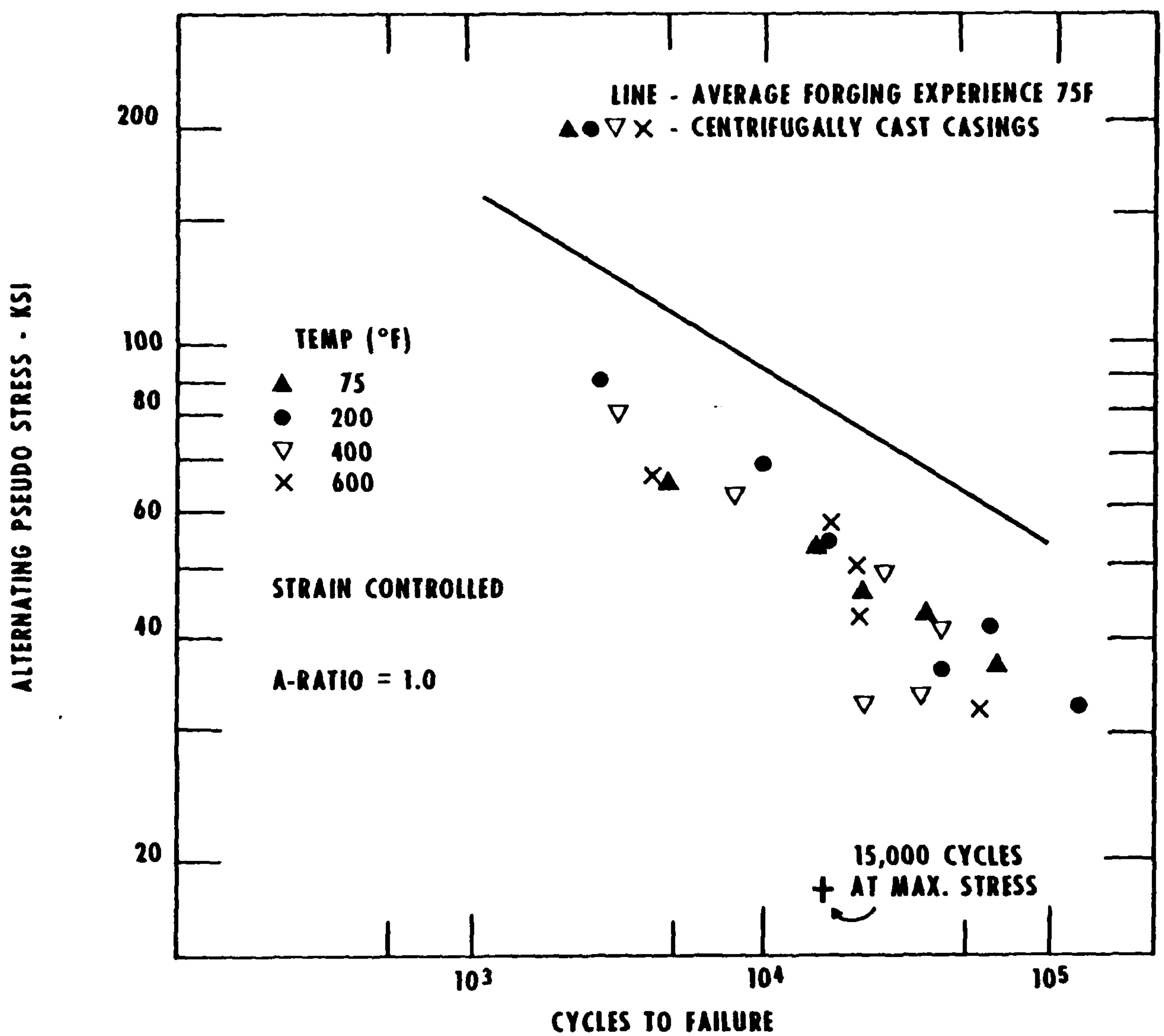


Figure 15. CRACK GROWTH RATE AS A FUNCTION OF STRESS INTENSITY AT ROOM TEMPERATURE

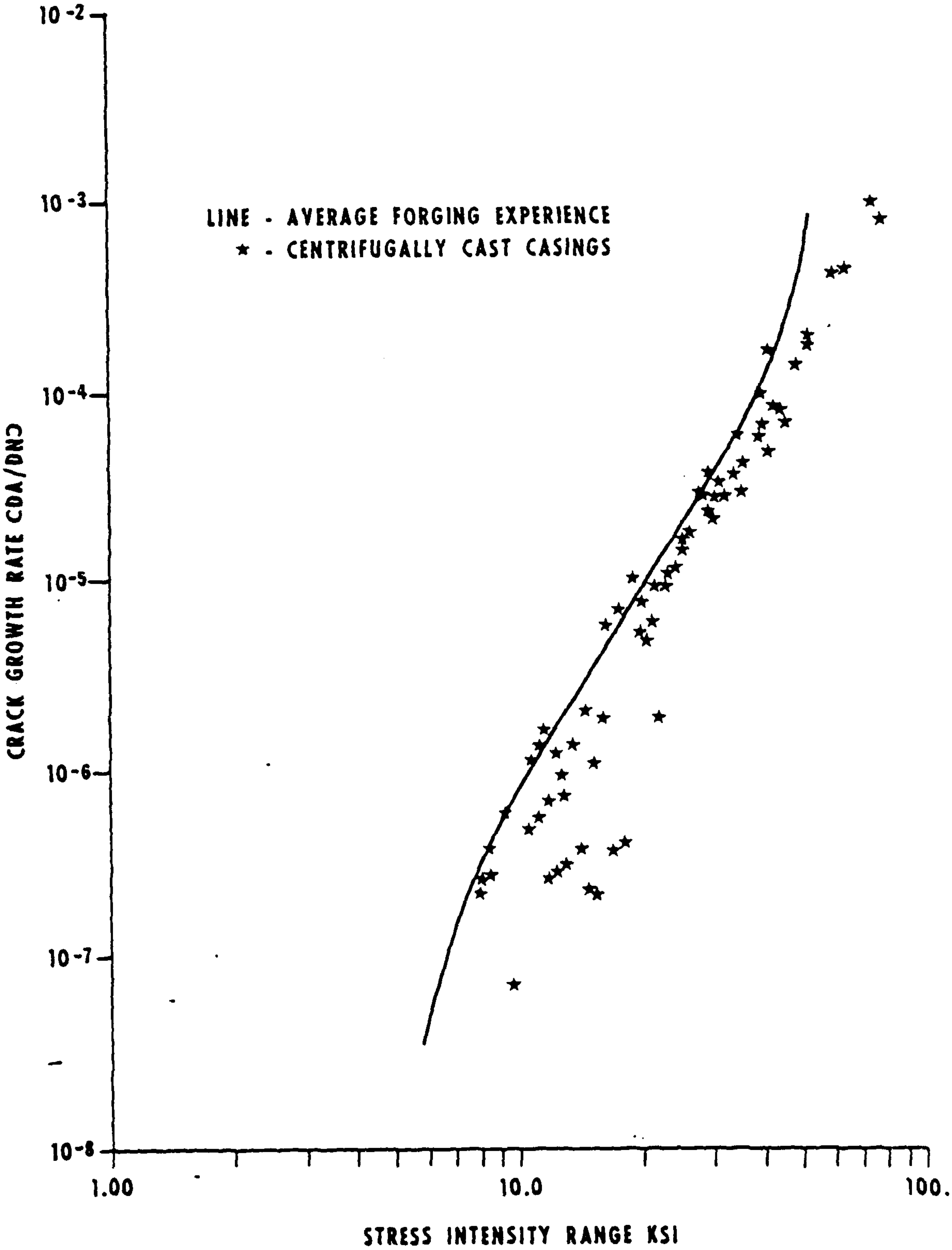
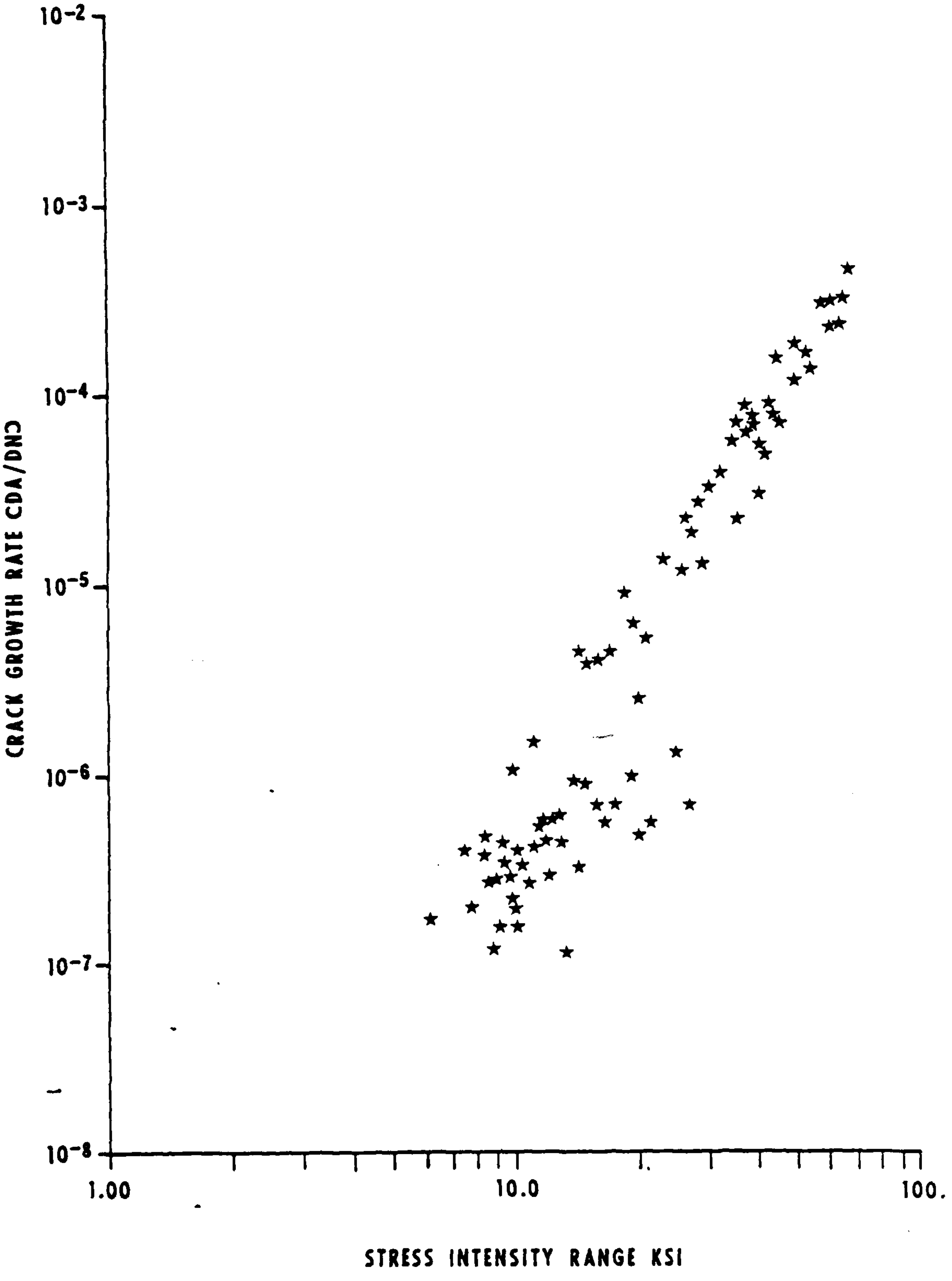
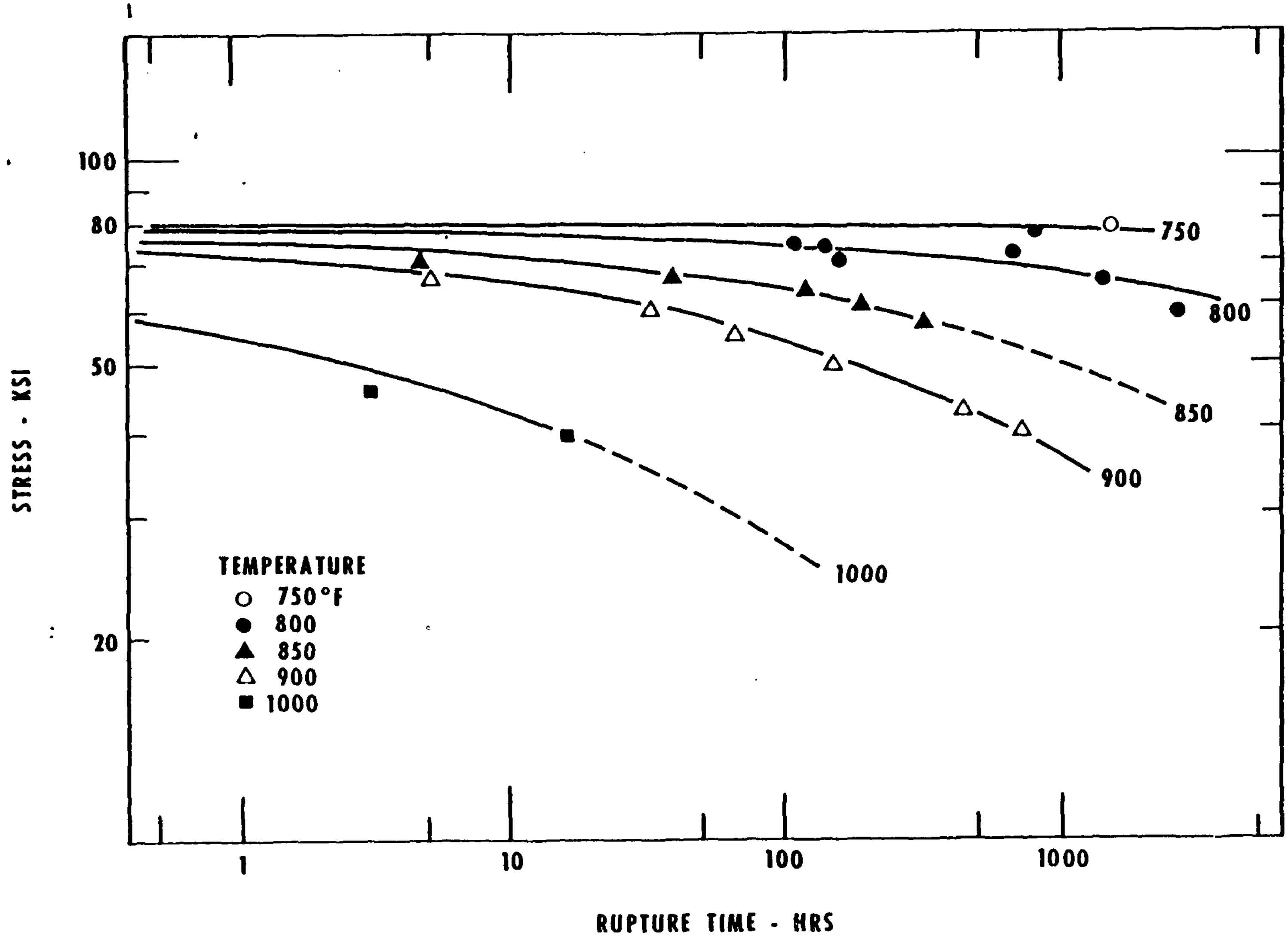


Figure 16. 600F TESTS OF CRACK GROWTH RATE AS A FUNCTION OF STRESS INTENSITY RANGE



17. STRESS-RUPTURE OF CAST Ti-6-4 Figure



BIOGRAPHICAL SKETCH

Mr. Mulliken was graduated from NYU in 1936 with a BS in Mechanical Engineering. From 1937 to 1959 he was employed by the Fairchild Engine Division of the Fairchild Engine and Airplane Corporation, Farmingdale, NY in various engineering capacities up to Chief Project Engineer. While there his direct responsibilities included development of both piston and turbine engines from the preliminary design through military qualification tests and technical support for the subsequent production and field service efforts.

From 1959 to 1964 he was employed by Thiokol Chemical in Brigham City, UT and was responsible for technical definition of major rocket motor components and ground support equipment and for coordination with suppliers of these items.

He left Thiokol in 1964 joining NASA at Langley Research Center where he was involved in research on high temperature materials and on fiberglass and their application to rocket motors.

Since 1974 Mr. Mulliken has been with AVRADCOM's Applied Technology Laboratory at Fort Eustis, VA where he has been involved in development of lower cost production methods for components of small gas turbines and cost analyses of high volume production engines in this category.

Incl 2

Operational Environment for Navy Engine

by

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Introduction

Numerous problems have plagued Navy propulsion systems because their fleet operations have become more demanding than projected combat roles. An historical view shows gas turbine engines have been developed to meet proposed mission requirements and to exceed a 150 hour qualification test. It is also a fact that almost every development resulted in an initially low level of durability or component life. As deficiencies surfaced, product support programs enlarged to consume more resources while addressing component improvement.

Lately, the traditional approach to research, testing and evaluation has been challenged for not simulating actual service usage. Techniques which incorporate fleet stress levels are evolving and results are correlating well to those seen in the field. Thus, usage data has been identified as a primary requirement in defining design specifications for gas turbine engines.

In this paper I will describe the essential requirements which have driven propulsion system designs in the past. Then I will consider the development of an operational environment for Navy gas turbine engines. Finally, I will examine the impact of these actual mission cycles on design criteria and component lives.

Background

Naval aircraft propulsion systems are designed and evaluated to Request for Proposal (RFP) missions based on projected combat with specific weapons and avionics suite. These type of missions are illustrated by a power required time history shown in figures 1-4 and they have requirements such as maximum range, dash speed, combat and loiter times, rate of climb, etc. In every case, performance has been identified without regard to the downstream cost and life implications.

Gas turbine engines are indicative of this emphasis on meeting performance. The traditional gage for an acceptable engine has been the 150 hour model qualification test (MQT). This test is defined in either specification MIL-E-5007D (for turbojets/turbofans) or specification MIL-E-8593A (for turboshafts/turboprops) and consists of 25 cycles (150 hours) of a 6 hour schedule shown in figure 5. Emphasis during MQT was aimed at meeting specified performance and demonstrating surge free operation. On closer examination, figure 5 contains over 40% of the 6 hours at the

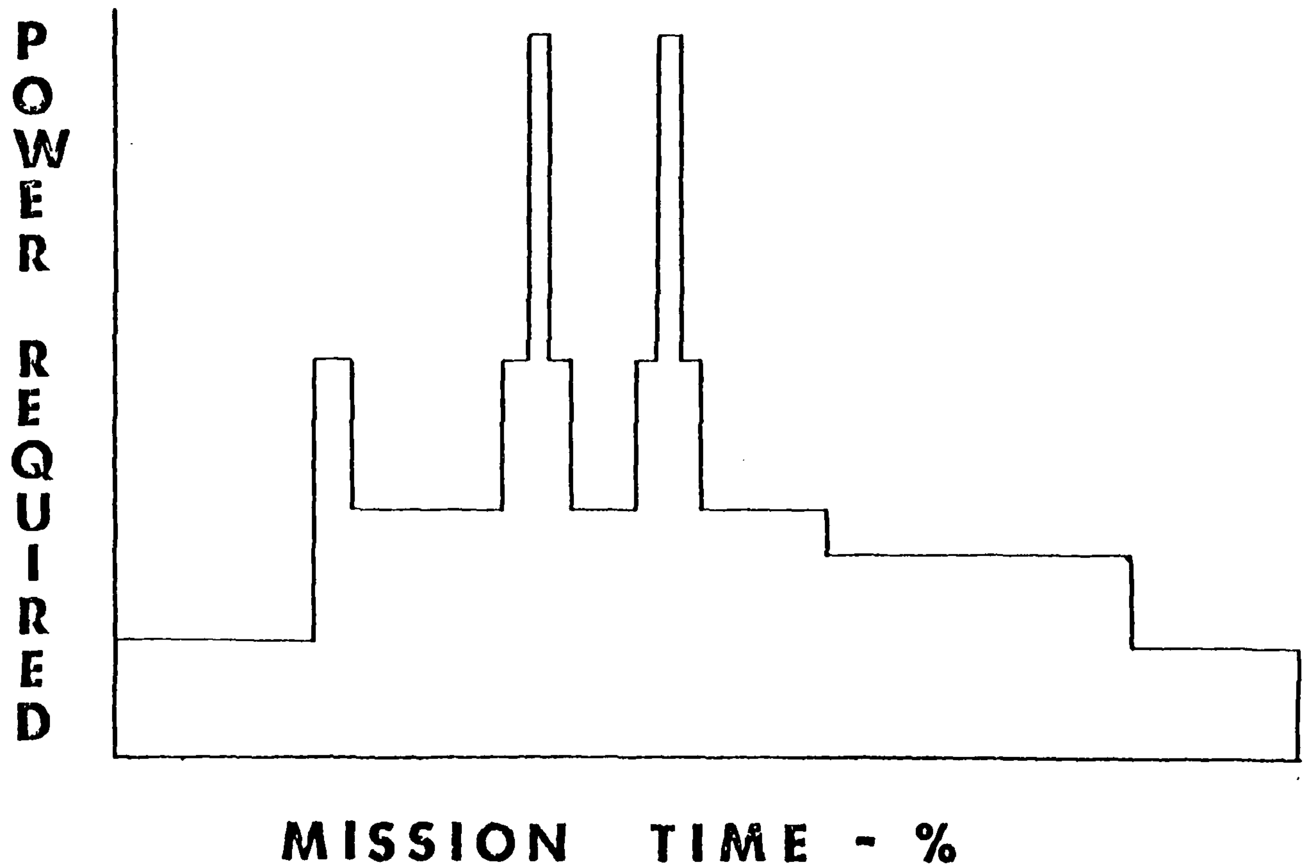


FIGURE 1. RFP F-18 ACM TRAINING MISSION PROFILE

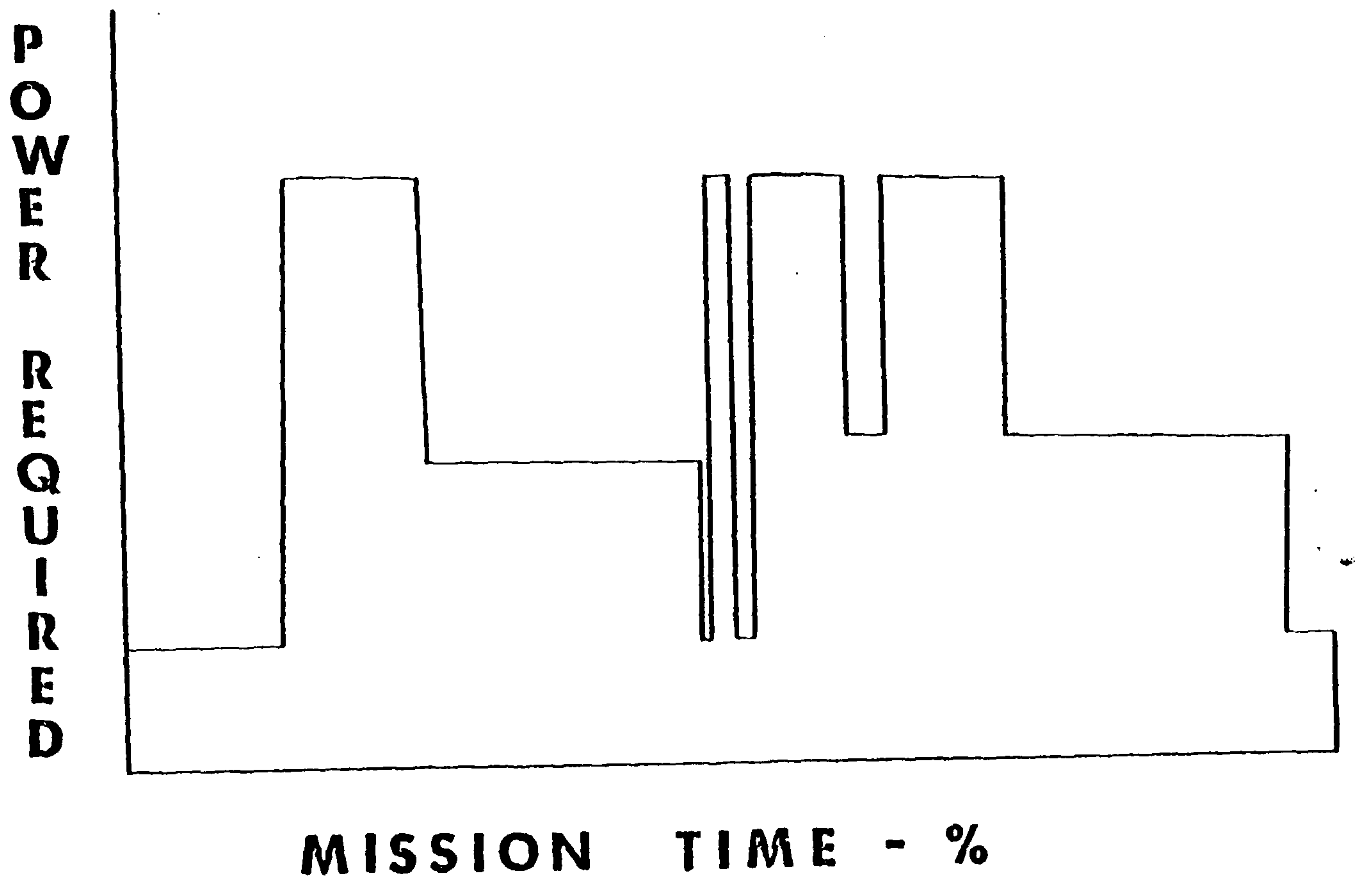


FIGURE 2. RFP AV-8B CAS COMPOSITE MISSION PROFILE

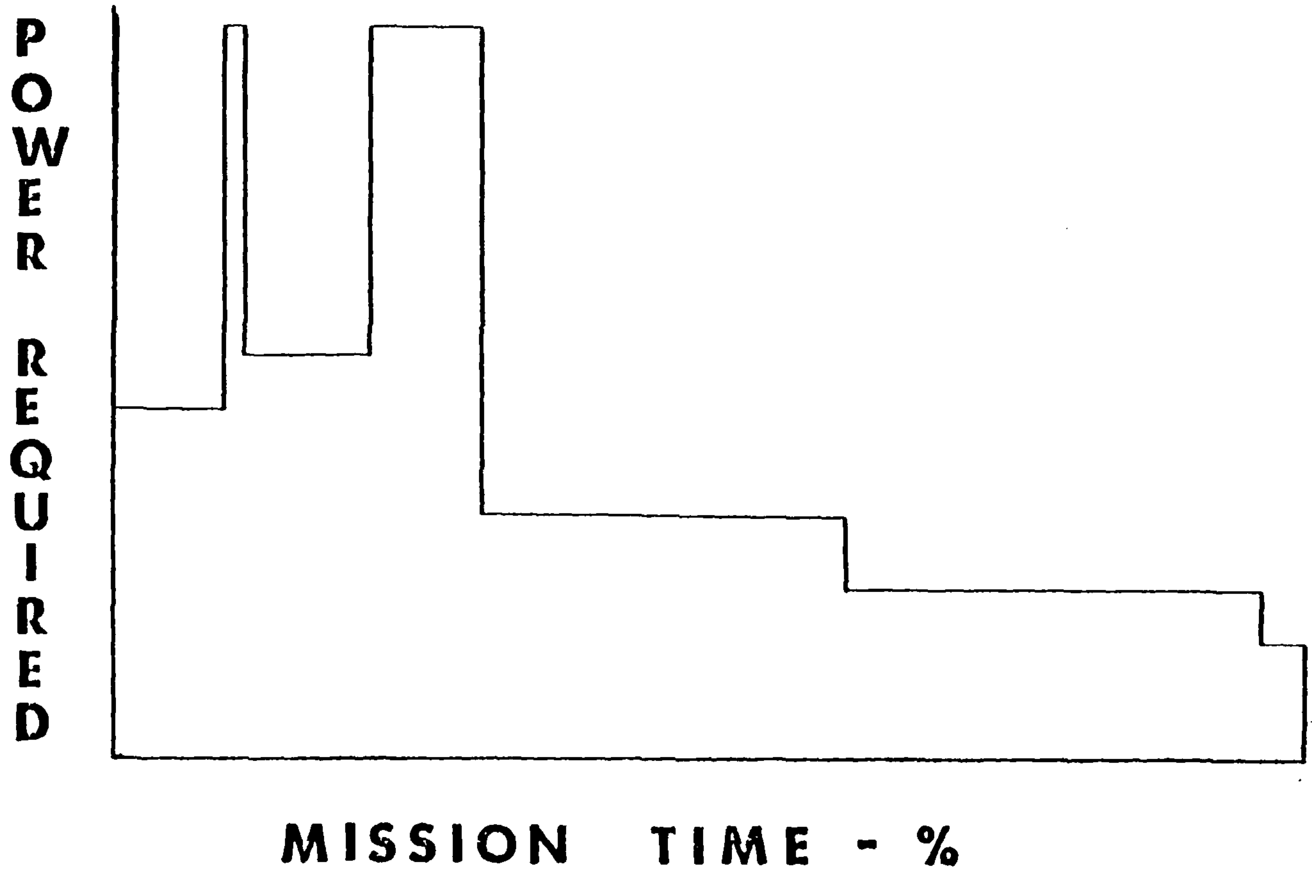


FIGURE 3. RFP F-14B DLI MISSION PROFILE

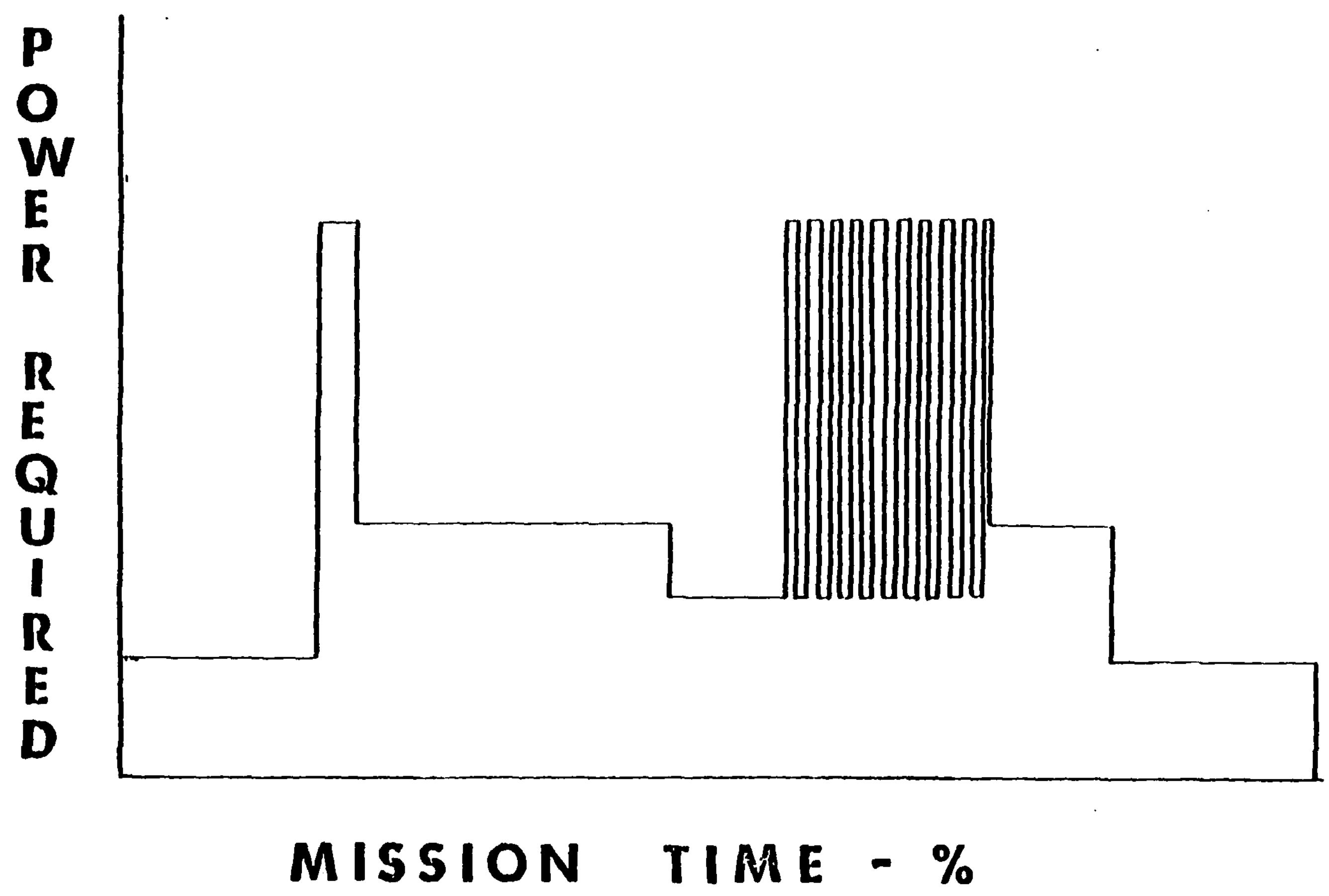


FIGURE 4. RFP A-18 CAS TRAINING MISSION PROFILE

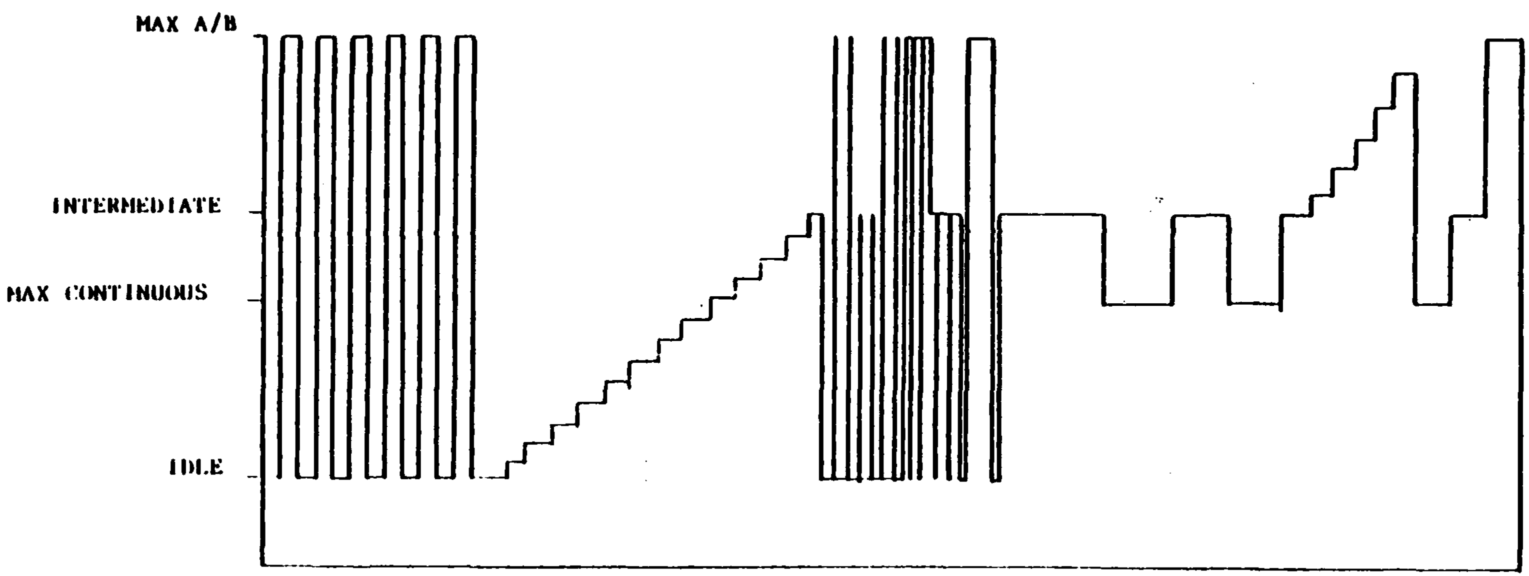


FIGURE 5. MIL-E-5007D QUALIFICATION CYCLE

operating conditions intermediate or maximum rated power. Testing at sustained maximum stress levels will show evidence of material creep and rupture, however the few cycles and short test duration cannot show any evidence of low cycle fatigue.

New engine tests have recently emerged to make use of the operational usage data in their techniques. Their names are indicative of their development, e.g., accelerated mission testing (AMT), simulated mission endurance testing (SMET), simulated accelerated flight endurance (SAFE), etc. Inspections of engines subjected to these new tests have correlated well with their counterparts in the field. Areas of concern, (noteably compressor and turbine disks shown in figure 6), in Navy engines such as the TF30, TF41, and F402 have seen their component lives reassessed because the operational usage was shown to be an order of magnitude more severe than previously believed in terms of low cycle fatigue. Table I addresses the various components affected and their different lives. In each component there has been a dramatic decrease in part life directly attributable to increased cyclic usage in the field.

SMET Development

As mentioned before, jet engines were tailored to meet or exceed MQT goals. It is now clear that there is not enough training and deployment usage data to which both Navy and industry could use in better design requirements for future engines. The SMET concept has evolved in order to supply this type of data in military specifications.

In the establishment of an operational usage data base, a fleet survey was conducted. Table II shows the list of squadrons visited. Pilot interviews provided a wealth of mission profiles for both training and deployed operations. To gain the widest experience for this data base, the entire range of pilots were interviewed. Responses differed significantly between inexperienced pilots and those with several thousand flight hours, however it was not possible to quantify the differences with respect to throttle movements at that time.

A representative mission or sortie was then created by combining all the unique and most frequently used legs throughout the mission category. There was very good agreement between pilots concerning mean parameter (engine) values on mission legs. These type of missions are characterized by the names in Table III.

Once the mission profiles were defined, flight data recordings were obtained to substantiate the engine duty cycle and establish a data base. Data from four different systems are shown in figures 7-10. Power required has been plotted as a function of the percent mission time. It is sufficiently obvious that in each case there are many more thermal and pressure cycles as a direct result of power lever movement. Furthermore, there is less time spent at intermediate rated power and above because of the dynamic nature in actual usage. This also suggests that more attention must be given to the operational environment realizing that power setting is directly analogous to component stress. These power excursions consume low cycle fatigue life at rates five to ten times greater than those expected during the RFP.

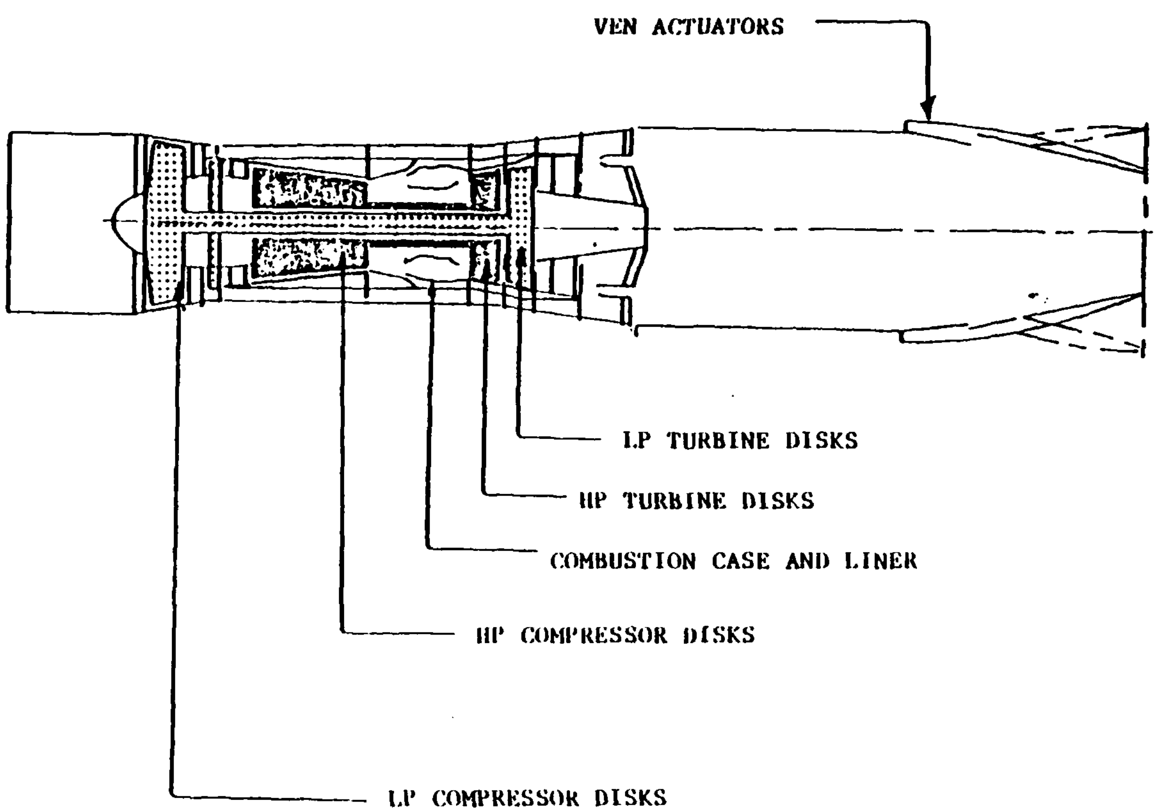
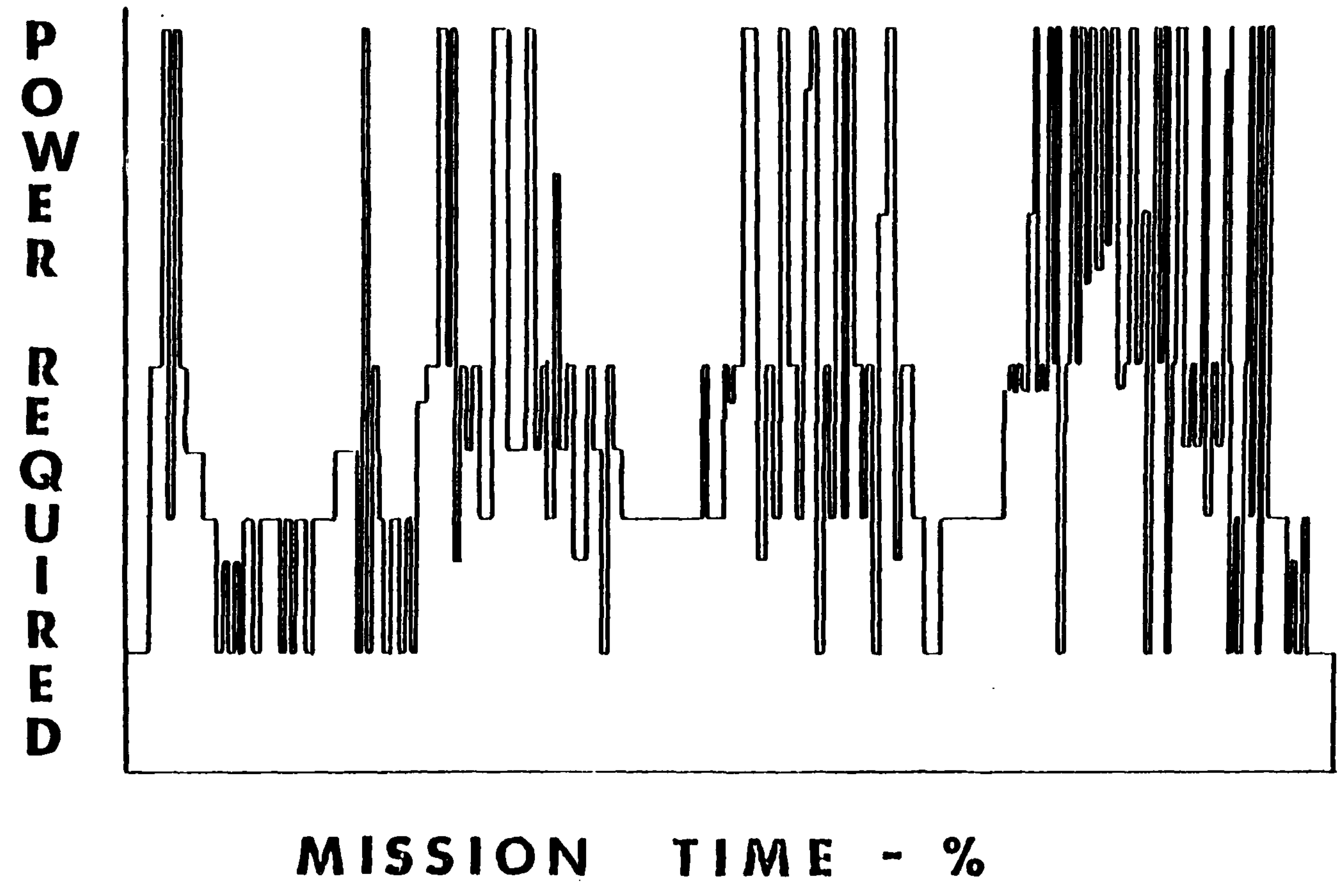


FIGURE 6. GAS TURBINE ENGINE LCF LIFE CRITICAL AREAS



FIGURES 7. YF-17 ACM FLIGHT DATA, RAPP

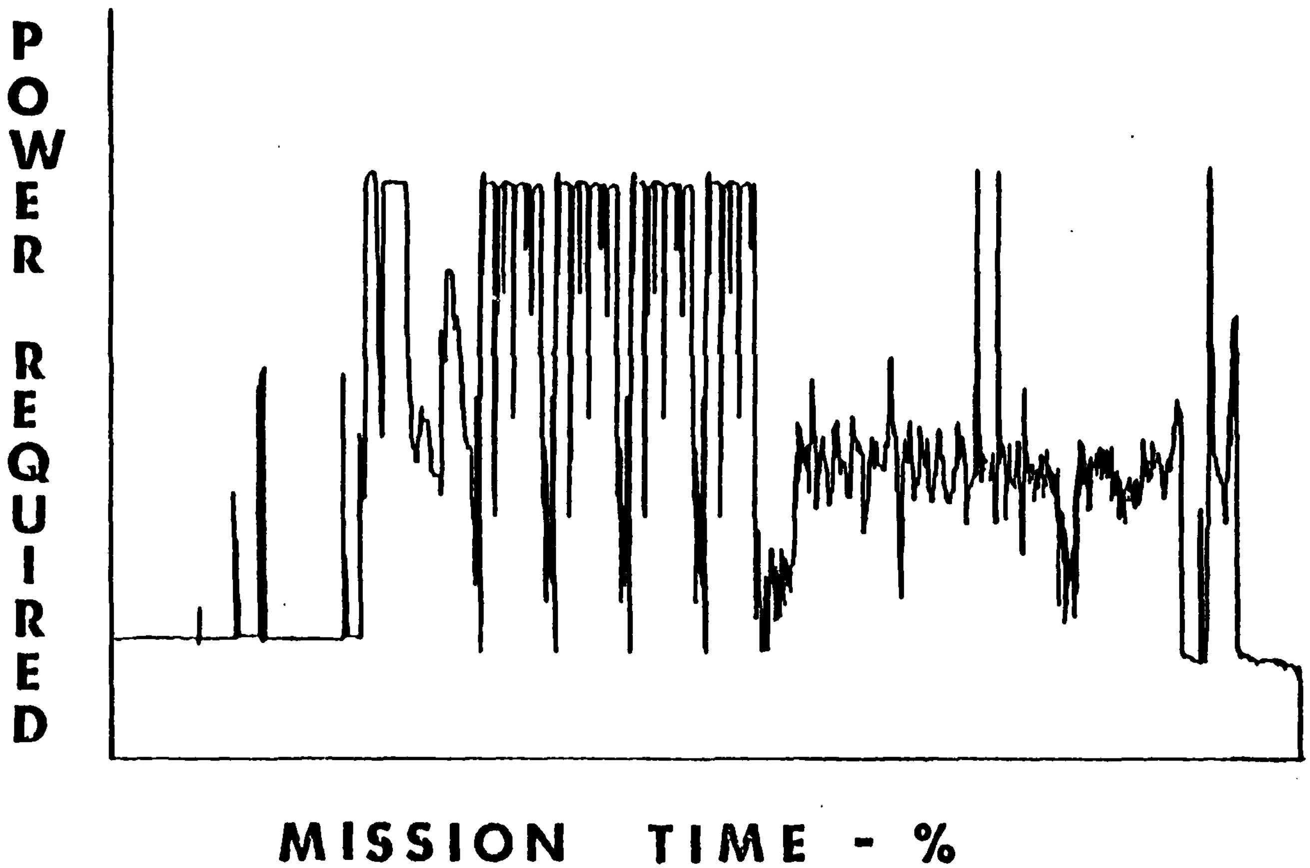


FIGURE 8. AV-8A CAS TRAINING FLIGHT DATA

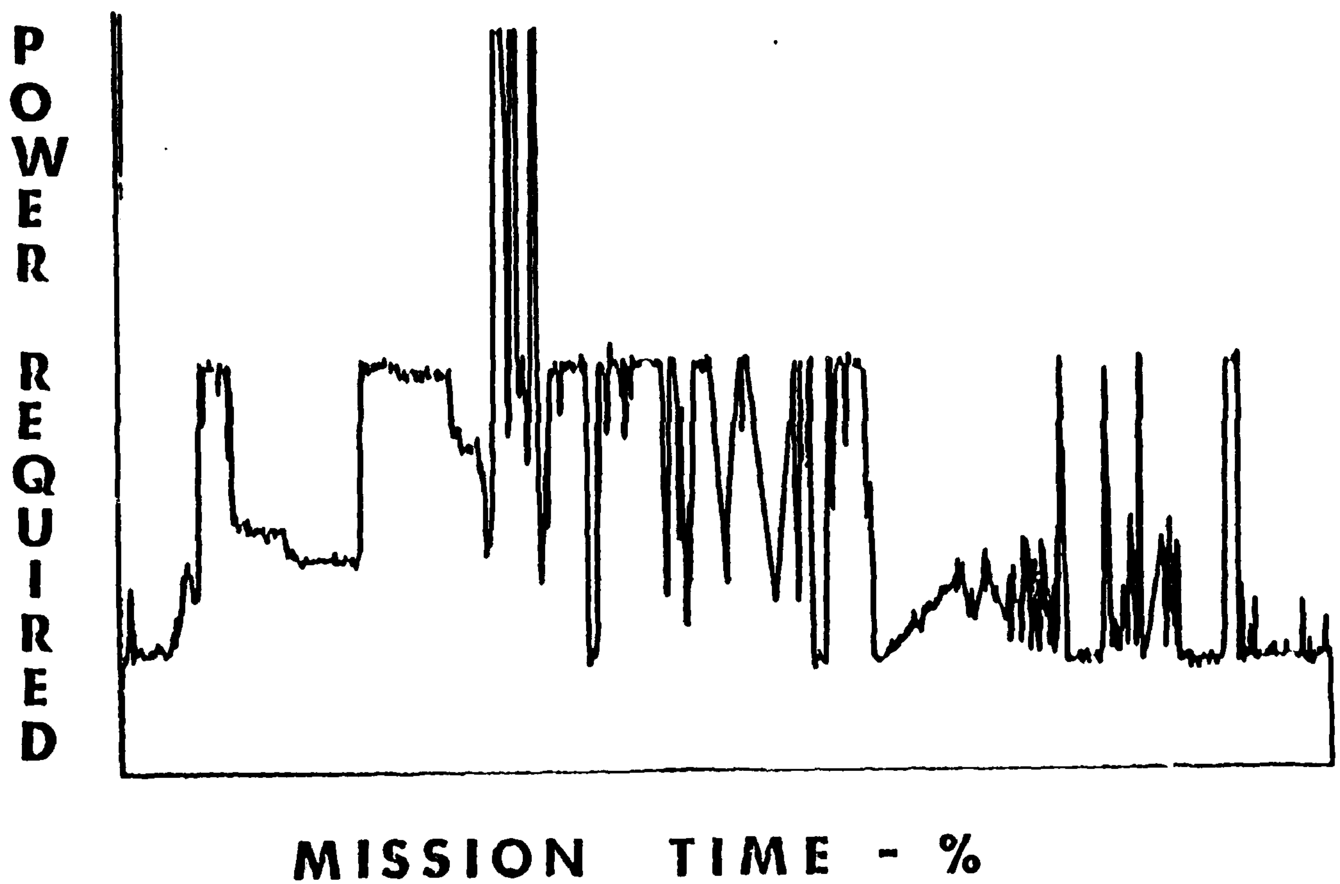


FIGURE 9. F-14A FAM TRAINING FLIGHT DATA

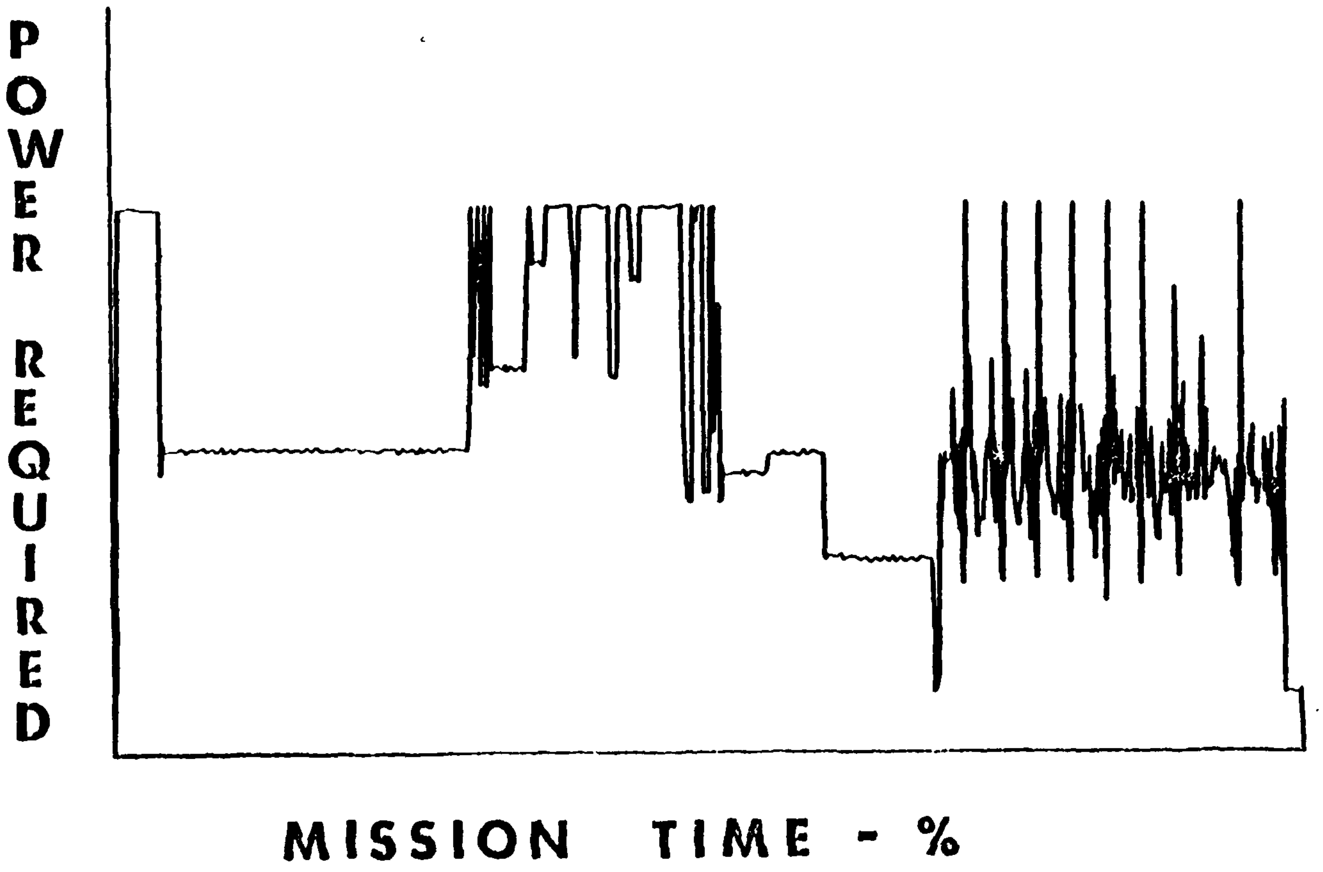


FIGURE 10. A-7E FAM TRAINING FLIGHT DATA

TABLE I

Turbofan Life Comparison (Old/New)

Component	TF30-P-412	TF41-A-2	F402-RR-402
1st Fan Disk	8700/900 (hrs)	no limit/3000 (hrs)	/1800 (hrs)
2nd Fan Disk	-	no limit/3000	-
1st, 2nd Fan Spacer	-	-	/1800
3rd, 4th Compressor Spacer	-	-	/1600
9th Compressor Disk	-	no limit/1500	-
10th Compressor Disk	4000/1400	no limit/1500	-
Burner Outer Case	/900	-	3300/1100
1st Turbine Disk	5600/900	no limit/1500	/1500
2nd Turbine Disk	8300/900	no limit/2500	-

T A B L E II

Squadrons Visited On Survey

VA	22, 34, 42, 75, 81, 83, 174
VMA	202, 203, 231, 513, 542
VF	1, 2, 14, 24, 124
VFA	51, 101, 122
VS	21, 22, 31, 38, 41
HSL	30, 31
HMA	169, 269, 369

TABLE III

Mission Category Types

Familiarization	Air Combat Maneuvers
Instrument	Air Intercepts
Navigation	Bombs and Rockets
Formation	Conventional Weapons
Field Landing Practice	Gunnery
Cross-Country	Tanker/Air Refuel

The final product of randomly sequenced number of missions weighted by percent use represents a SMET. The number of missions is directly proportional to the percent use. Table IV shows the comparison between a 150 hour MQT test and the F404, TF30, TF41 SMET results. Each of the SMET results have a significant increase in the number of cycles and much lower hot times (time at intermediate and above). Moreover the number of start to stop cycles is also greater by virtue of the SMET's longer length. This suggests the operational environment with its necessary repetition is overstressing jet engines and their components. Since these duty cycles are causing distress in the field, then designing to these cycles must in turn give cost and life savings downstream.

Impact of the Duty Cycle

A set of revised F404 duty cycles (adjusted for aircraft aerodynamics) were examined in terms of severity to component lives prediction. The results of the five times greater cycling appears as increased travel and wear on all variable geometry actuators and linkage, especially the variable exhaust nozzle. The travel in these actuators increased by seven times the design value. There was also a 60% increase in the idle time offset by a similar decrease in afterburning time with less wear on the afterburner fuel pump and control system. Other areas where redesign is required to maintain durability specified contractually are summarized in Table V.

As a result, these changes to the design will be incorporated and then qualified to a SMET for production. With a compromise between life, cost and performance, an overall product can be produced and at the same time completely suitable for service introduction. One may pose the question then "How much will this life cost the Navy?" and "Can the Navy recoup these funds downstream?". An estimate of development necessary to meet these new mission specifications has been offered at $\$37\overline{M}$ by the contractor. If the lives of the hot section alone could be increased in actuality by 500 hours (mean life operating time), this effect has been shown to decrease the number of overhauls and repairs thus yielding $\$460\overline{M}$ and $\$374\overline{M}$ savings in operations and support cost over a twenty year life. Therefore a clear cost advantage provides the means to both fund the life development, look for further ways to lower operating and support (O&S) costs and give an incentive to industry to reach these goals.

Concluding Remarks

It is clear that RFP missions are not truly representative of fleet engine usage with respect to defining engine structure lives and to service suitability. MQT has also been shown to be less severe in terms of thermal and pressure cycling when compared with recorded flight data of fleet missions.

Mission profiles were gathered from fleet activities and the flight data from these missions established an engine usage data base. SMET's have been constructed via the data base to make a more accurate assessment of current Navy jet engine component lives. In each case the cyclic evidence has been overwhelming with dramatic reduction in component life.

TABLE IV

Endurance Test Comparison

Operating Condition	MIL-E-5007	F404	TF30	TF41
Idle Power	22	126	274	223
Part Power	58	528	588	493
Intermediate	34	79	106	34
Afterburning	$\frac{36}{150}$	$\frac{17}{750}$	$\frac{32}{1000}$	$\frac{--}{750}$
Throttle Excursions				
Idle to Intermediate	625	2740	9720	1499
A/B to A/B	400	1987	2962	--

TABLE V

Impact On Component Design

Castings - beef up life limited areas

Frames - beef up life limited areas

Combustion Liner - additional cooling air

HPT Nozzle - additional cooling air

HPT Blade - redesign cooling circuit

Performance - increased cost, weight, and SFC; decreased FN

The impact of these duty cycles has been shown to be increased wear and distress to engine controls and components. There is a great cost advantage seen in operation and support if component lives are met. Future gas turbine designs will have more accurate information (duty cycle) in military specifications.

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THE USE OF INTERACTIVE GRAPHICS AS A

CAD/CAM TOOL DURING F404 DEVELOPMENT

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May 1975

INTRODUCTION

Computers have been in use in major industries for more than two decades, but until recently, the activity in engineering and manufacturing has been separate and independent. The availability of relatively low cost mini-computer graphics systems with application software aimed at drafting, design, and numerical controlled machining has provided a major connecting link between design and manufacturing.

Unlike most industries where computer graphics started in the engineering function, the need for such a system at the Aircraft Engine Group (Lynn) of the General Electric Company was determined by both Engineering and Manufacturing; in fact, the urgent need in Manufacturing accelerated the acquisition schedule in Engineering by a few years. Use of interactivecomputer graphics as a "Computed Aided Design/Manufacturing" (CAD/CAM) tool dates from 1973 when a mini-computer system was evaluated in an actual working environment on drafting, tool design, and n/c programming applications. A cross-functional "CAD/CAM Council" coordinated activity, and provided overall direction to the development and evaluation effort. A system was finally configured, specified, and purchased in 1974, justified by cost savings data accumulated during the evaluation period. It was also during this period that software application software requirements were defined and communicated to all the competing graphics system suppliers. We like to think that we played a significant part in the development of n/c programming graphics software capability through detailed distribution of requirements.

This system is now integrated into our design process, so that each new engine cross section is defined and stored in the graphics system. This data base is then available to all, whether they be stress analysts, thermal analysts, n/c programmers, tool design draftsmen.

THE BASIC SYSTEM

Our IAG Systems have three key components which are all necessary for successful CAD/CAM applications - they are Hardware, Software, and Data.

Hardware

The basic hardware consists of mini-computers, magnetic disc storage units, magnetic tape drives unit and cathode ray tube (CRT) terminals. Using the CRT terminal, the user is able to communicate interactively with the computer by using simple English words and pointing to diagrams on the CRT. The terminal consists of a desk on which there is a CRT display which shows a part or a tool path as it is being defined. (See Figure 1) In front of the CRT there is a tablet which contains up to 220 programmable function keys. The top row of keys contains verbs such as "insert", the second contains nouns such as "point" and the third row contains adjectives or modifiers such as "end of" or "intersection of". This system of input combines the ease and speed of pushbutton systems with the flexibility of keyboard systems. The area of the tablet below the rows of keys is interactive and corresponds to the CRT display. An electronic design pen

moved over this area will cause a corresponding movement of a cursor on the CRT display. The remaining component of the terminal is an alpha-numeric CRT display which records the user's instructions to the computer and its reply back to the user.

Other peripherals on these systems are a hard copy unit which duplicates images from the CRT display, a paper tape punch and reader, electrostatic printer/plotters, high speed communications links, and an interactive drawing board which can communicate to the computer in the same way as the CRT terminal (Figure 2). A variety of other computers and precision plotters are an integral part of our CAD/CAM system. At present we have 16 CRT terminals in the Lynn Plant, 10 used by Engineering and 6 by Manufacturing (Figure 3). This does not include literally hundreds of printing and CRT terminals used in a time sharing mode on our mainframe computers.

Data

Our data are the engine parts represented by geometric entities to describe their configuration. Part geometry is the most frequently used data in our business. The IAG Systems produce most of the data and are also the biggest user of it. Our extensive data base gives each user a tremendous jump on the lead time to perform his task and greatly reduces confusion and errors involved in redrawing contours and computing dimensions.

Software

Our IAG Systems contain extensive geometry problem solving software implemented in highly human engineered ways so as to minimize training and to maximize existing expertise in functional organizations. Although the multi terminal disc operating system is complex and sophisticated, it is "well hidden" from the user. The software is proficient at creating and editing geometric shapes as well as moving, rotating, scaling, and calculating their properties.

USE OF THE SYSTEM

The IAG Systems are simple to use because of the inherent advantages of interaction and graphics. An interactive system allows the user to "talk" with the computer and lets him interject his judgment or ask for help an any point in the computer's solution of a problem. Graphics allows the user to see an instantaneous picture of what he is creating at every step in the process.

In addition to these inherent advantages, the system has been human engineered so that the user "talks" to the computer in the same language he would use to precisely instruct a fellow human. For example, if the user wished to have a line join the ends of two existing lines, he would touch the following three keys with the electronic pen: - "insert", "line", "at the end of". He would then point with the electronic pen to the appropriate ends of the two lines and the third line would be automatically created. We cannot overstress the importance we have found for the use of "plain English" versus "Computerese" in terms of training and general acceptance of the system by

people who haven't been exposed to computers and are naturally somewhat afraid of them - people such as draftsmen, tool designers, methods engineers, etc.

The creation of N/C cutter tool paths is almost as simple. After defining the cutter, the user asks the computer to list a menu containing options such as:

1. Select check/drive surface
2. Select drive boundary
3. Lathe macro
4. Etc.

The user then selects the appropriate instruction by typing in its number and pointing to the surfaces to be machined. Commands such as spindle speeds, feed rates, etc. can be inserted at any point. The tool radius and centerline tool path are displayed on the screen as this process progresses.

TYPICAL F404 APPLICATIONS

Engineering Summary

The process of designing a jet engine is characterized by iteration, requiring tremendous volumes of calculation and judgment. IAG and the rest of our total CAD/CAM system do most of the calculations, and experienced designers and engineers contribute the judgement. The increased calculating power of IAG results in improving the productivity of analytic tasks by 3.5 to 1 on the average with many spin off benefits

such as quality, accuracy, and cycle time reduction. This productivity increase provides great leverage to engineering. For "structured" tasks such as the process of producing various assembly drawings, it typically results in a cost savings. For "non-structured" tasks such as stress and vibration analysis, the productivity savings can be converted to doing a more thorough design job, resulting in a better design the first time (See Figure 4).

The F404 (see Figure 5) is giving us good evidence that the savings for doing the job right the first time is substantial. The time from contract go ahead to first complete engine to test was 14 months - a new record at the Aircraft Engine Group. Yet the engine assembly process has been characterized as the easiest and smoothest of all. In a large way, this is due to the thorough configuration and stack up studies done on IAG before parts were released.

Drafting

With our interactive graphics system, the bulk of early design/configuration work is done on the CRT, from flowpath layout through precisely detailed part contours. The final result is filed into the data base and simultaneously plotted on mylar (see Figure 6). The mylar copy is used to make the finished drawing. Since today, we can usually achieve higher productivity rates in analytic tasks, most of the dimensions, notes, tables of data, etc., are added to the drawing manually. It is important to realize that this is not just an image on the CRT, it is precise geometric data in the computer memory which can be manipulated to suit our needs; the CRT merely makes the data visible. To date, there are 294 major parts of the F404 engine

represented in the data base, comprising the entire cross-section of the engine. All parts for a given engine in the data base are defined relative to their position from two common axes, the centerline and the front of the engine. As a result, we are able to call up several parts and have them placed in assembled position automatically. Thus, sub-assembly, assembly, module, clearance and stackup drawings can be produced automatically by feeding the data base for the appropriate parts into an automatic plotter. A typical engine assembly drawing using these data bases is shown in Figure 7. These drawings can be produced in about 12% of the time formerly required, and the quality far exceeds anything that could be reasonably achieved manually. Savings in drafting time are readily apparent if one considers that typically, each part on the engine was drawn nine times for various engineering drawings, and this does not even count the many more times it is done for manufacturing process instructions, tooling, stress analysis, thermal analyses, etc.

Design Review

We have found that both the CRT and scaled plots of the engine cross-section are very useful tools for design reviews - formal or informal. The engineer essentially has a very precise drawing of his components, and can visually spot errors in stacking, blends, undersize fillets, etc. in much the same way that these errors are often spotted after the part is made. The system also allows the user to zoom in and magnify any local area of the screen to any magnification. This enables the draftsman to check for dimensional errors and provides a verification

capability that has never existed. The system can produce many different views in a matter of minutes. Permanent copies ("hard copies") can be produced in seconds with very rough accuracy, in minutes with accuracy of $\pm$ .010", or within hours to accuracy of $\pm$ .002".

Stackups

The ability to display an assembly of various components is also used to advantage in axial stackup calculations. In this application the draftsman or the engineer has all the components of interest displayed on the screen. In the time it would normally take him to describe the task, he is able to identify the areas where he wants clearances and obtain their values. This process results in a thorough verification of both the overall engine design and the assembly process.

Finite Element Analysis

The parts of a jet engine are subjected to severe heat transfer, stress and vibration conditions. One mathematical tool used to calculate the effects of these on a given part is "Finite Element Analysis". Essentially, in this technique, the part is subdivided into a number of small rectangles or triangles which are analyzed separately. The total effect on the part is the sum total of all the subdivisions (Figure 8). The analysis is performed by a large computer but until graphics was used, the geometric input into the analysis program was manual and tedious. To obtain the input it was necessary to make a large scale accurate drawing of the part shape. An engineer then drew in the elements, with smaller and more numerous

elements near suspected problem areas. Each element was then numbered and the coordinates of the nodal points were measured manually. All this information was then converted into a punched card deck which was then input to the mainframe computer for analysis. If the analysis indicated a problem area, the part geometry was changed in that area and the entire process repeated.

The availability of Interactive Graphics and the part data base has changed all that. Now the data bases of the parts to be analyzed are called up on the CRT display without having to redraw the part. In the examples of the F404 Compressor Disk (Figure 8), the finite element grid has been generated semi-automatically through software which we developed. The engineer has the ability to change any portion of this grid pattern if he so desires. The elements are numbered and the precise coordinates of the nodal points are obtained automatically by the graphics system. This information is output from the system in a format that requires no human intervention before being put in the mainframe computer for analysis. Should the analysis indicate that the part geometry requires modification, this is done rapidly at the CRT terminal and the entire process repeated. The time taken to obtain the finite element model data has been reduced by 75% with the use of Interactive Graphics.

Kinematics

The analysis of connected moving parts has traditionally been so tedious and complicated by manual drafting techniques that it is often

accomplished through the construction of "hard" models. Models are expensive, slow to acquire, and lack flexibility in evaluating alternatives. Our IAG System has allowed us to thoroughly analyze the kinematics of two very critical F404 engine systems earlier in the program and at greatly reduced cost. The "variable geometry" stator vanes are rotated based on engine operating requirements with a complex set of 3 dimensional linkages and to very exacting tolerances. Likewise, the variable exhaust nozzle contains a complex actuating linkage and interwoven "leaves" which overlap as the nozzle closes down (See Figure 9). Graphics allows us to accurately determine the required motion of the actuators (pistons) and to evaluate clearances with savings in the 8 to 1 range.

Mass Properties

The feature of our graphics system that has seen the widest application in all organizations is that of "Mass Properties" (Figure 10). This feature automatically gives the perimeter, area, center of gravity, and moments of inertia of any cross section. In addition, the properties of the cross section when rotated about any axis to form a solid are also given: exposed surface area, volume, weight, center of gravity and moments of interia. Applications range from weight calculation to contour roll die design. In our business, weight is a primary design parameter. During the design of engine, weights of each part, and each design alternative, must be calculated. In the past this had been done manually, by breaking each part into simple geometrical shapes the volumes of which could be calculated. The mass properties are now obtained in 75% less time, and just as importantly we know how we are doing much earlier in the program.

Tool Design

Our tool designers have found the availability of the F404 Engineering data bases invaluable. These data bases are used for a number of tooling applications. Typical of two-dimensional applications are templates and glass layouts (Figures 11 and 12). In both these applications computerized plotting is also used. This ensures, in the case of product inspection, that the finished part is inspected to engineering's computerized definition of the part in addition to its being manufacturing to the definition.

The three-dimensional capabilities of the graphic system are also used to advantage in tool design. The system can rotate the part in any direction and take measurements from any desired datum, thereby eliminating days of manual calculations. An example of such an application is an electro discharge machining fixture (Figure 13). The interactive graphic system's ability to define and manipulate complex shapes is used in the design of dies and punches. The mathematical definition of these surfaces enables the designers to define the shape with a precision which is impossible with manual drawing techniques (See Figure 14). For example, the surface can be intersected in any plane and its shape obtained precisely. Thus, the tool designer has complete freedom in the selection of the position and number of inspection templates.

The design time for these applications has been reduced to between 12 and 25% of the time formerly taken and glass layout costs have been reduced 60%.

NC Part Programming

CAM started when the computer was used to assist the part programmer to generate tapes which instruct numerical control machines to perform manufacturing operations. A part programming language called APT (Automatically Programmed Tools) soon became the industry standard. The language evolved into a powerful and versatile one but it had two inherent disadvantages. The first is that the user must learn a language with its own syntax and grammar. As most experienced manufacturing personnel have relatively little computer experience, they were exposed to many concepts which were alien to them. The other disadvantage was that the computer did not give the programmer a visual representation of what he was creating at every step in the process. He therefore had to mentally visualize the tool path as he was programming. The combination of these disadvantages either prevented capable machine shop personnel from becoming part programmers, or else they made the learning time unacceptably long.

These difficulties of the APT system have been resolved by the interactive graphics system. A menu of instructions each identified by a number and the use of programmed keys has virtually eliminated the system problems. In addition, visual verification on the CRT of every step in the process has replaced the mental visualization formerly required. As a result, the time required to train a methods man to make N/C tapes has been reduced by a factor of 6 and tapes are produced in one third the time taken by conventional APT programming. Typical of the F404 parts which are machined by N/C using tapes generated by the Graphic's System is the

Stage 1 Fan disc shown in Figure 15. The corresponding tool paths are shown in Figure 16.

In the days when we relied on APT for all our part programming, the programmers were organized into a central programming unit. Methods personnel requested the centralized programming unit to create N/C tapes for them. This resulted in communication problems and a lack of responsibility for ownership of the part being machined by N/C. By installing an interactive graphic system in the planning office of one of our machine shops, we have been able to decentralize the programming. Now the person planning the tooling and machining of the part also creates the N/C tape. This eliminated the communication problems and has reduced the amount of effort and time needed to optimize the tapes.

THE FUTURE

Much remains to be done to improve the efficiency and flexibility of the system in handling our current and future applications. Most of the work needed is in the system software, which we will develop either in-house or in cooperation with the interactive graphics system manufacturer.

When developing new applications for a system, which has as much potential as the interactive graphics CAD/CAM system, it is easy to fall into the trap of chasing quixotic applications. We have, therefore, been careful to take a pragmatic approach to our development. Instead of "Brainstorming applications we have acquainted personnel throughout Engineering, Manufacturing, and Quality Control functions of the capabilities of the system. Based on their needs, we have found that, as the system capabilities have increased,

applications suggested themselves. These were evaluated, and if a payback was established, the applications were incorporated into the system.

We have a very decentralized CAD/CAM organization - both users and developers. Users, in all cases are the people who used to perform the job manually. In one notable case, IAG has allowed us to further decentralize N/C tape making activities. Some of our user groups are unionized, however they have been cooperative and even helpful in expanding application. One of the most successful attributes of IAG is its ability to avoid another entire layer of specialization in the organization. Development is also decentralized to assure a high level of control and accountability. At the same time, we do not wish to give the impression that the development of CAD/CAM is treated with a laissez-faire attitude. We have established steering committees and a roadmap which gets regular reviewing as does the status of specific development programs.

We have pioneered in many areas of CAD/CAM, and we are proud of that. We have gained from our efforts. We are optimistic about the future, and committed to the use of interactive graphics throughout our organization.

FIGURE 1

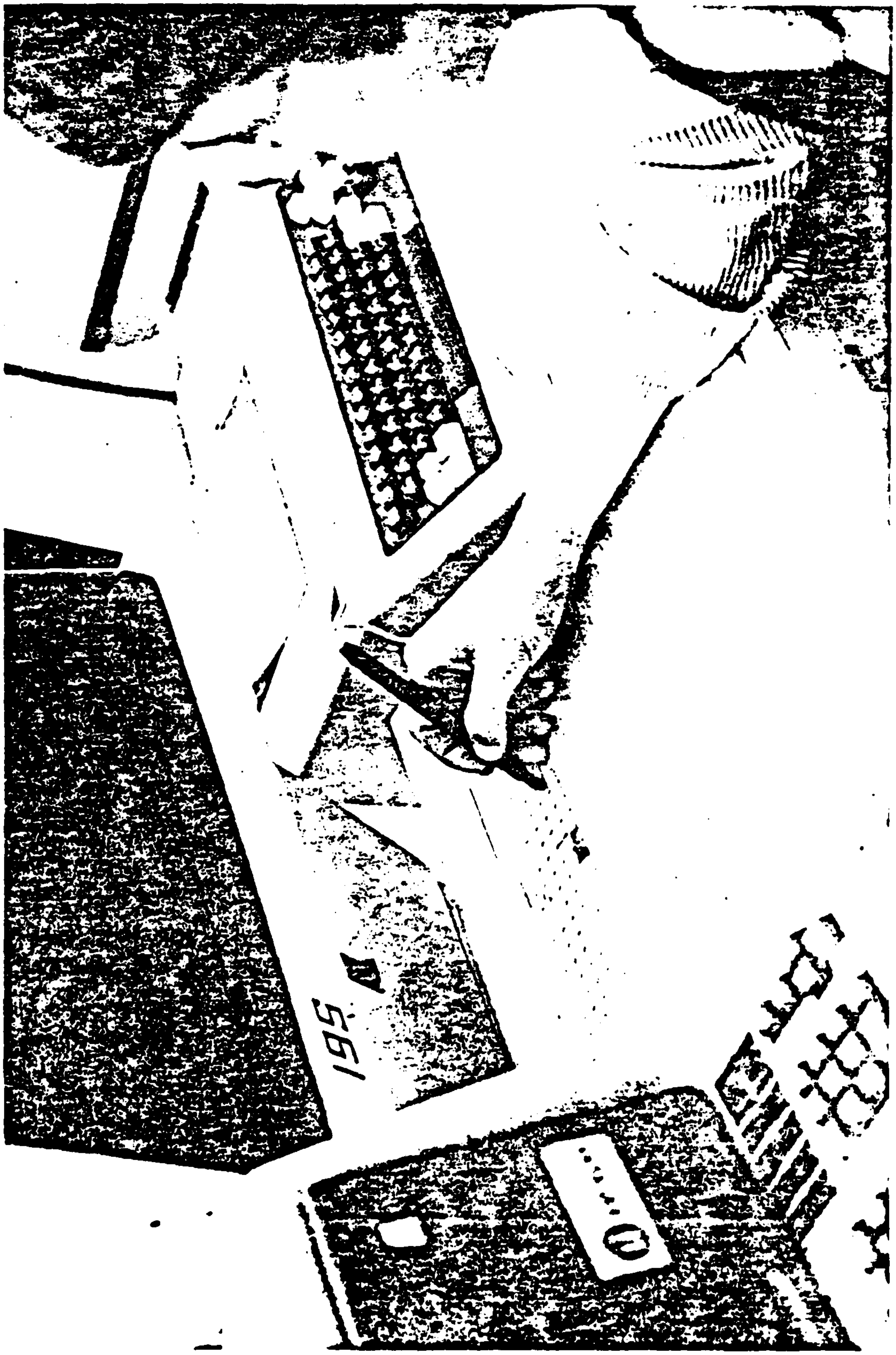
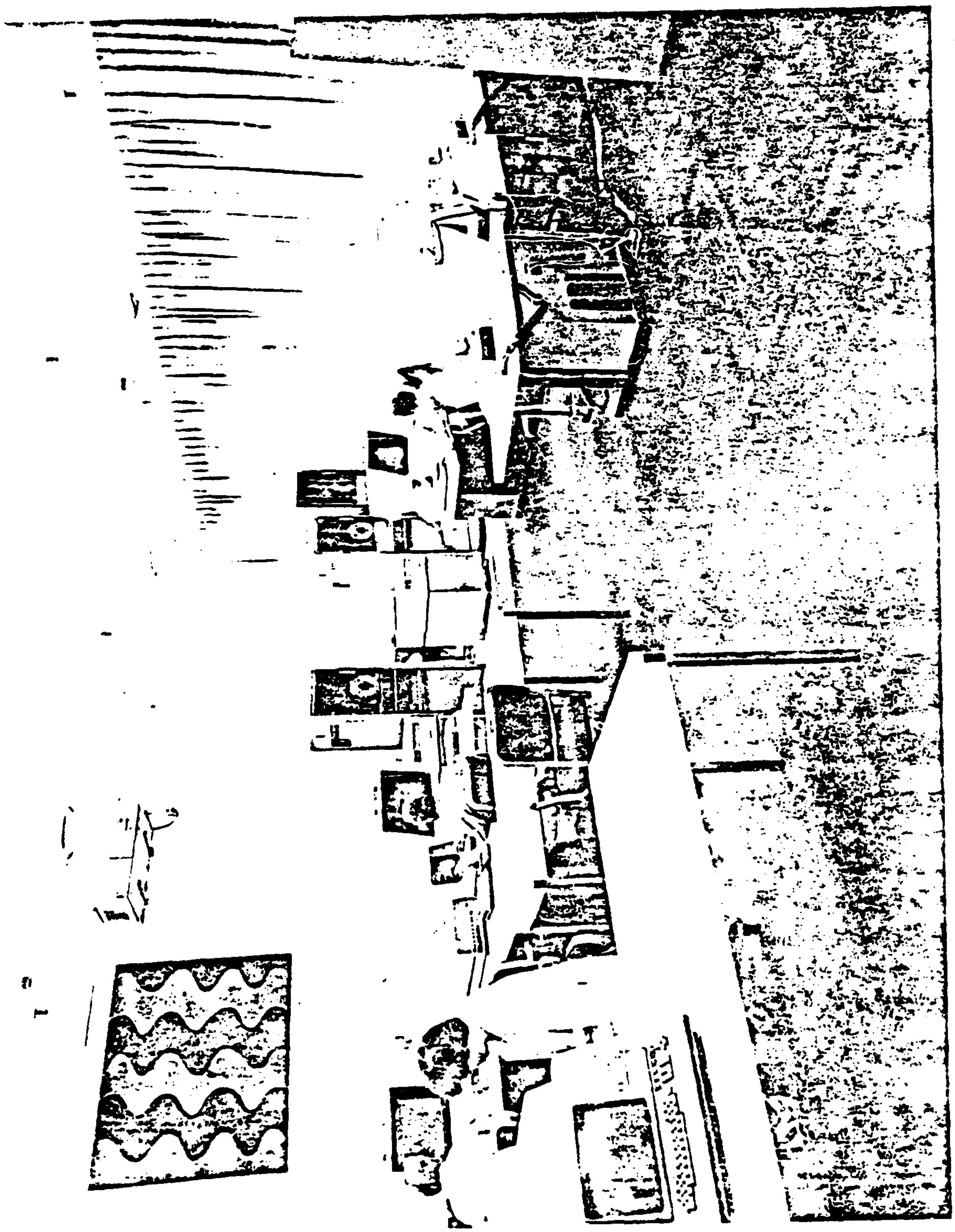


FIGURE 2

FIGURE 3



"DO THE JOB RIGHT THE FIRST TIME"

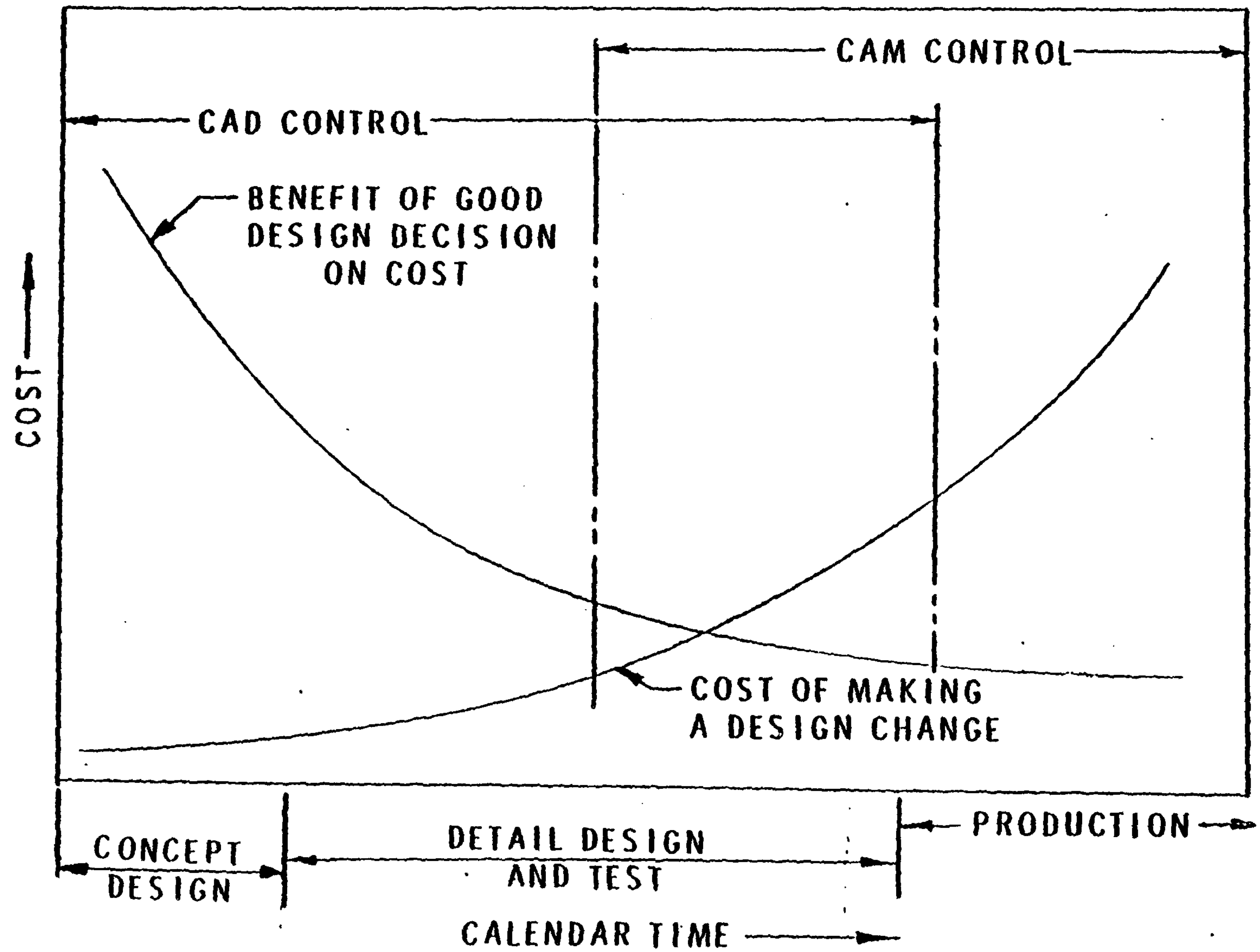


FIGURE 4

FIGURE 5

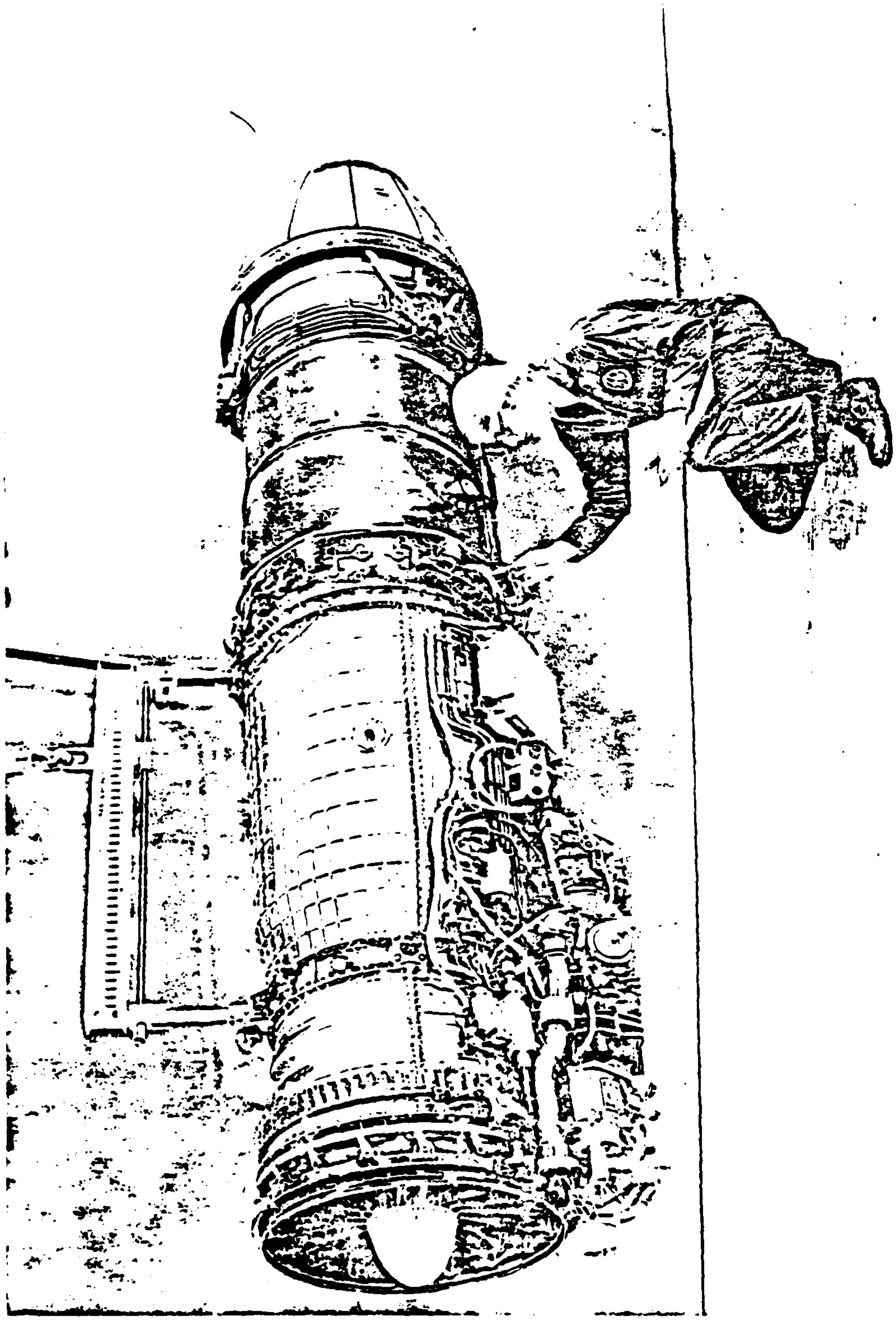
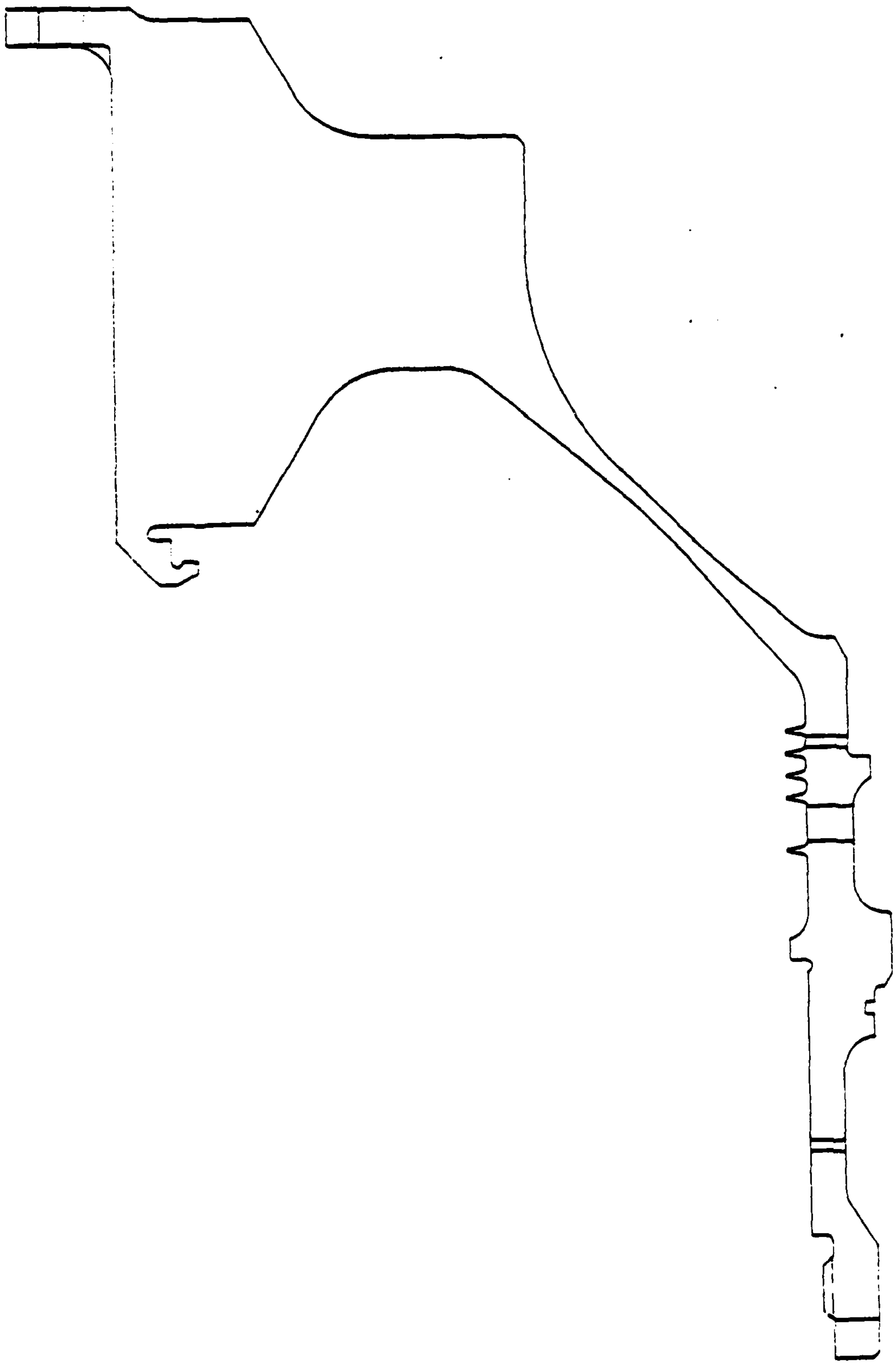


FIGURE 6



F404 FAN STG 1 DISK

TYPICAL ENGINE CROSS SECTION
FROM IAG DATABASE

FIGURE 7

FINITE ELEMENT MODELING

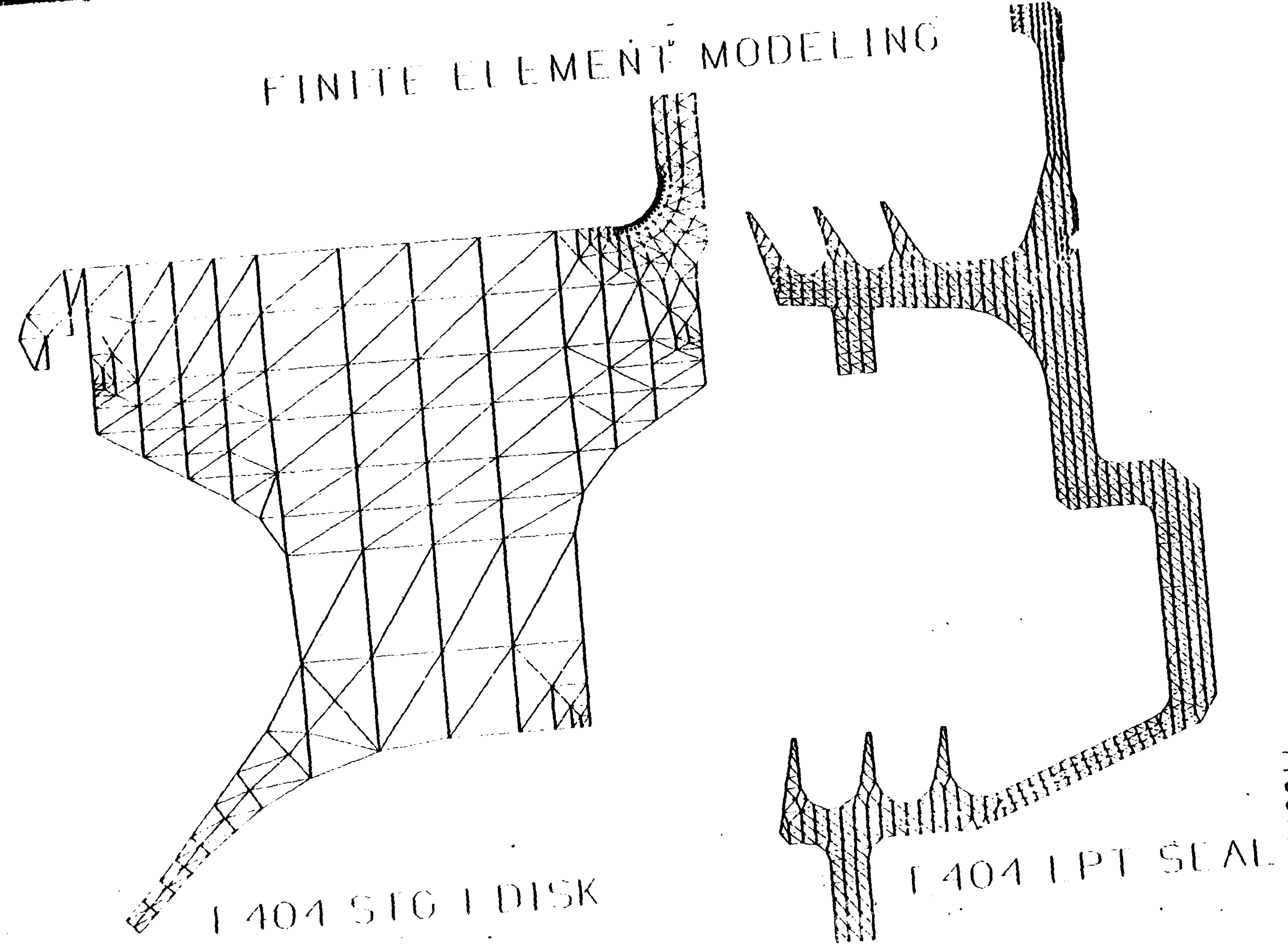


FIGURE 8

FIGURE 9

KINEMATIC DESIGN STUDY

F404 VARIABLE EXHAUST NOZZLE

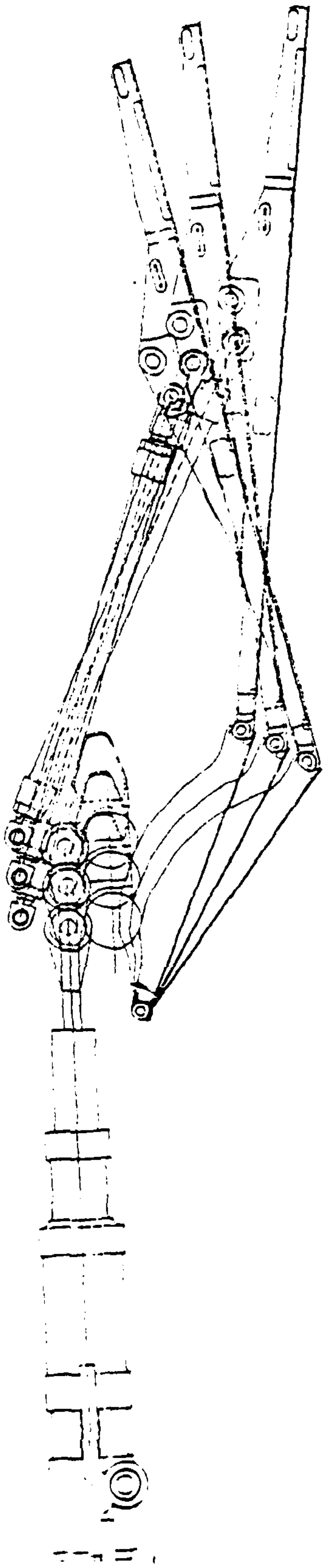


FIGURE 10

IAG MASS PROPERTIES OUTPUT

PARTNO	=	6034T00G02F
DATE	=	10-6-76
XREF	=	0.0000 IN

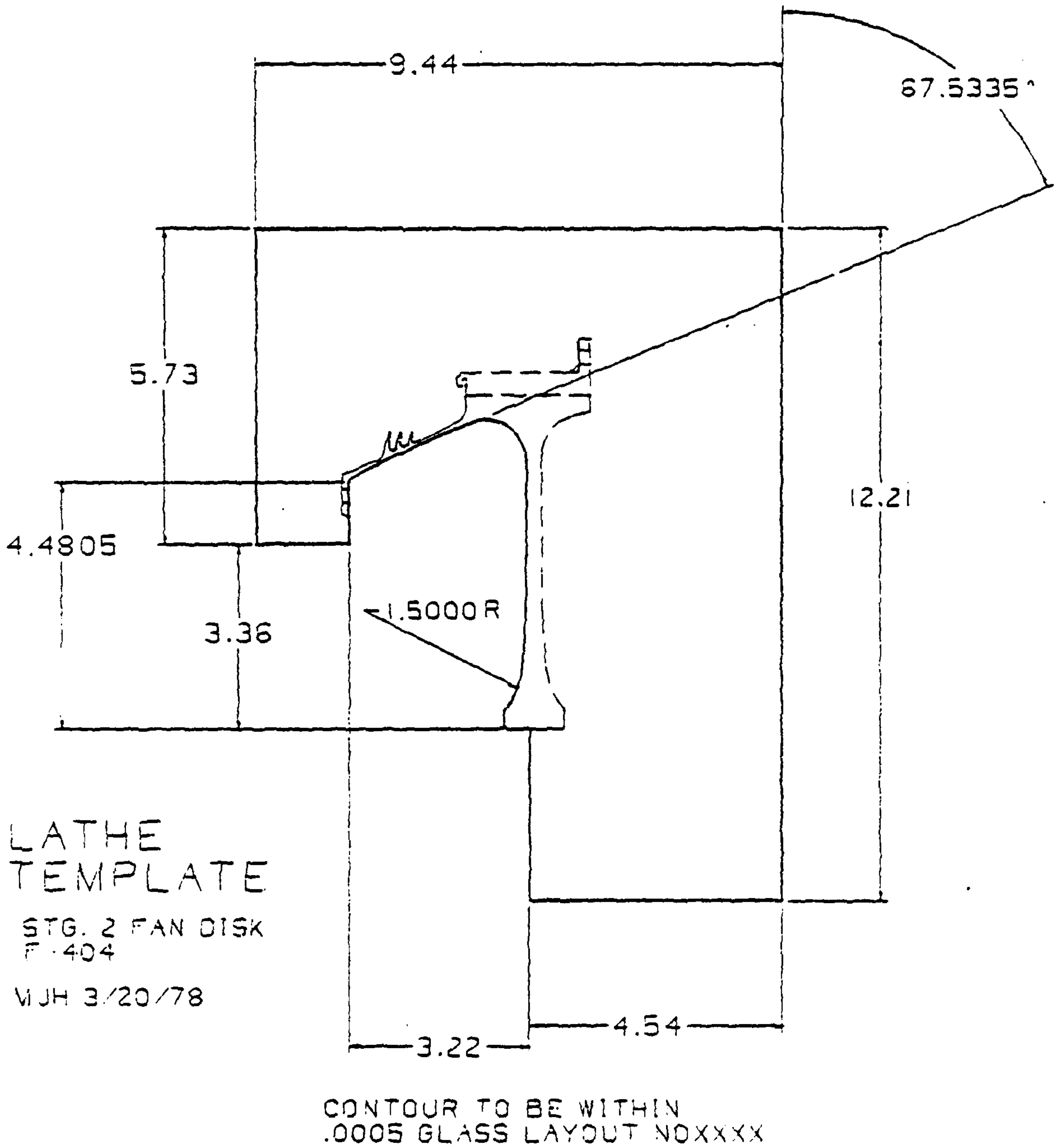
PLANE SECTION - ASSUME GDF IS IN INCHES

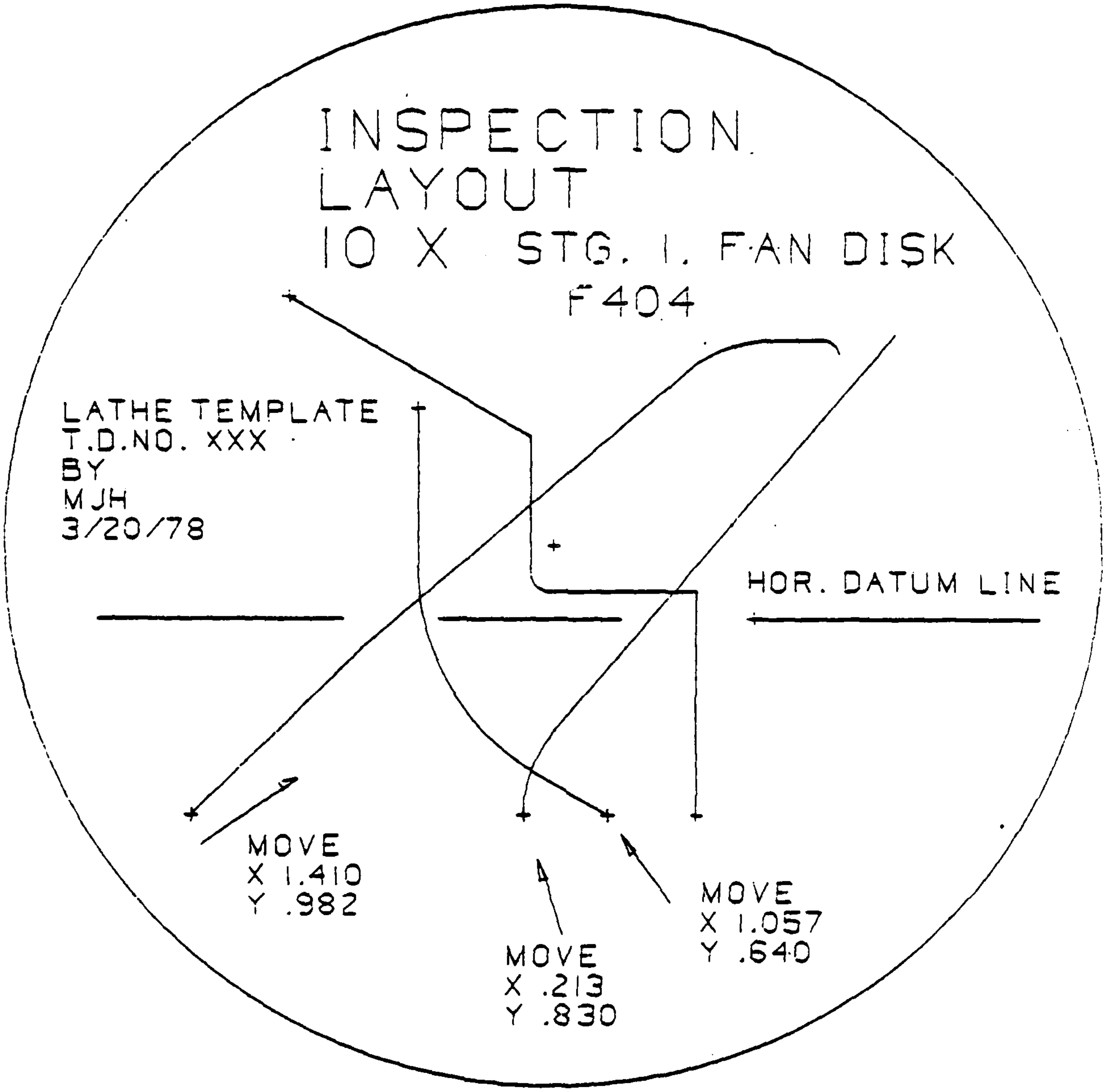
LGTH	=	12.3239 IN.
AREA	=	1.3261 IN. **2
CGX	=	28.9144 IN. FROM X-REF
CGY	=	2.5214 IN. FROM X-AXIS
AMX	=	8.9281 IN. ** 4 ABOUT X-AXIS
AMXC	=	0.4978 IN. ** 4 ABOUT CGY
AMY	=	1109.2196 IN. ** 4 ABOUT X-REF
AMYC	=	0.5887 IN. ** 4 ABOUT CGX

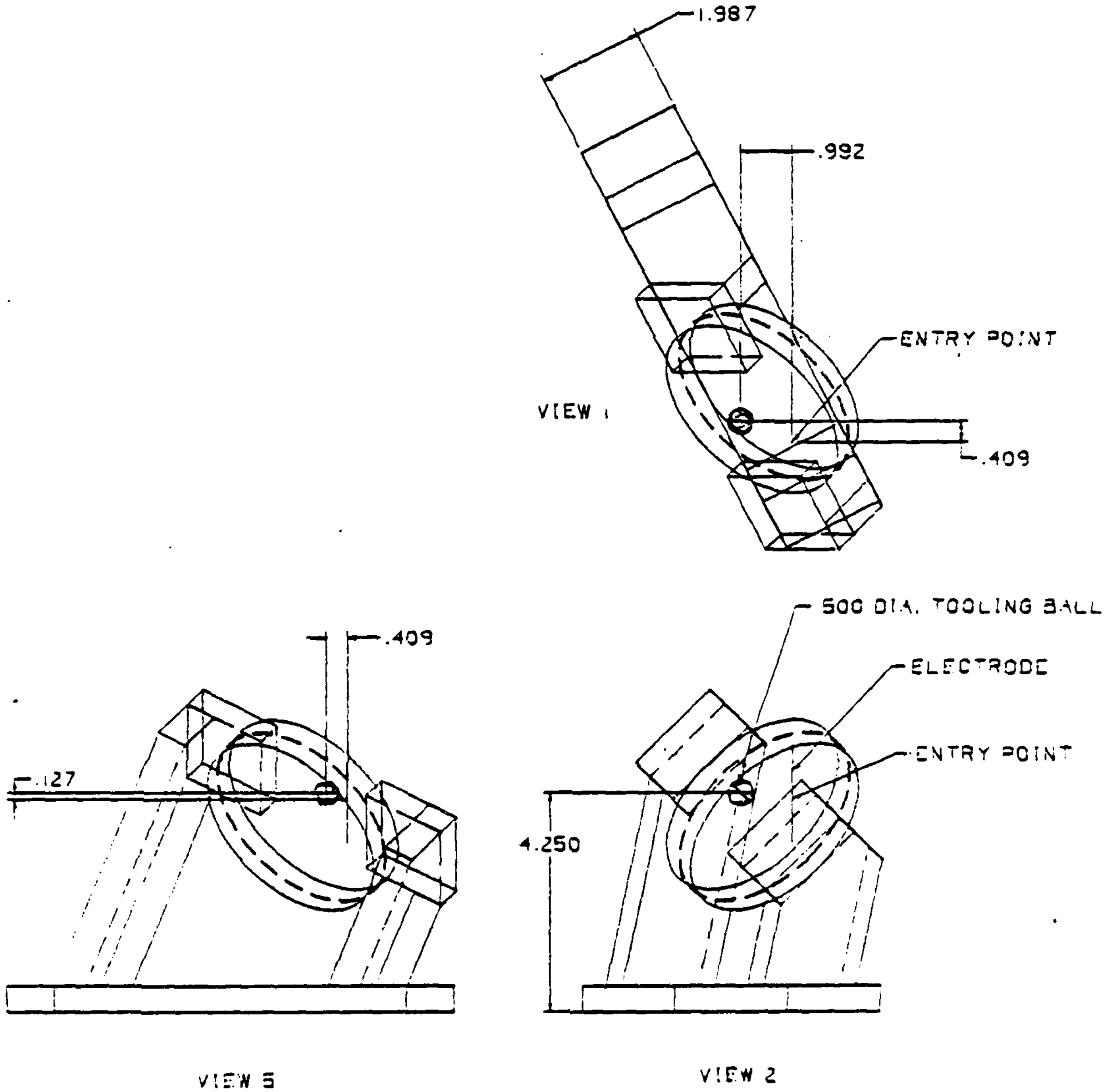
ROTATED SOLID - DENSITY = 0.1610 LB. PER CU. IN.

SURF	=	1.887164 IN. ** 2 (ALL EXPOSED SURFACES)
VOL	=	21.0083 IN. ** 3
CGX	=	28.9863 IN. FROM X-REF
WGHT	=	3.3823 LBS. (1535.5782 GRAMS)
MMX	=	25.3450 LB. IN. ** 2 ABOUT THE X-AXIS
MMY	=	2857.5319 LB. IN. ** 2 ABOUT THE X-REF
MMYC	=	13.7622 LB. IN. ** 2 ABOUT CGX

FIGURE 11

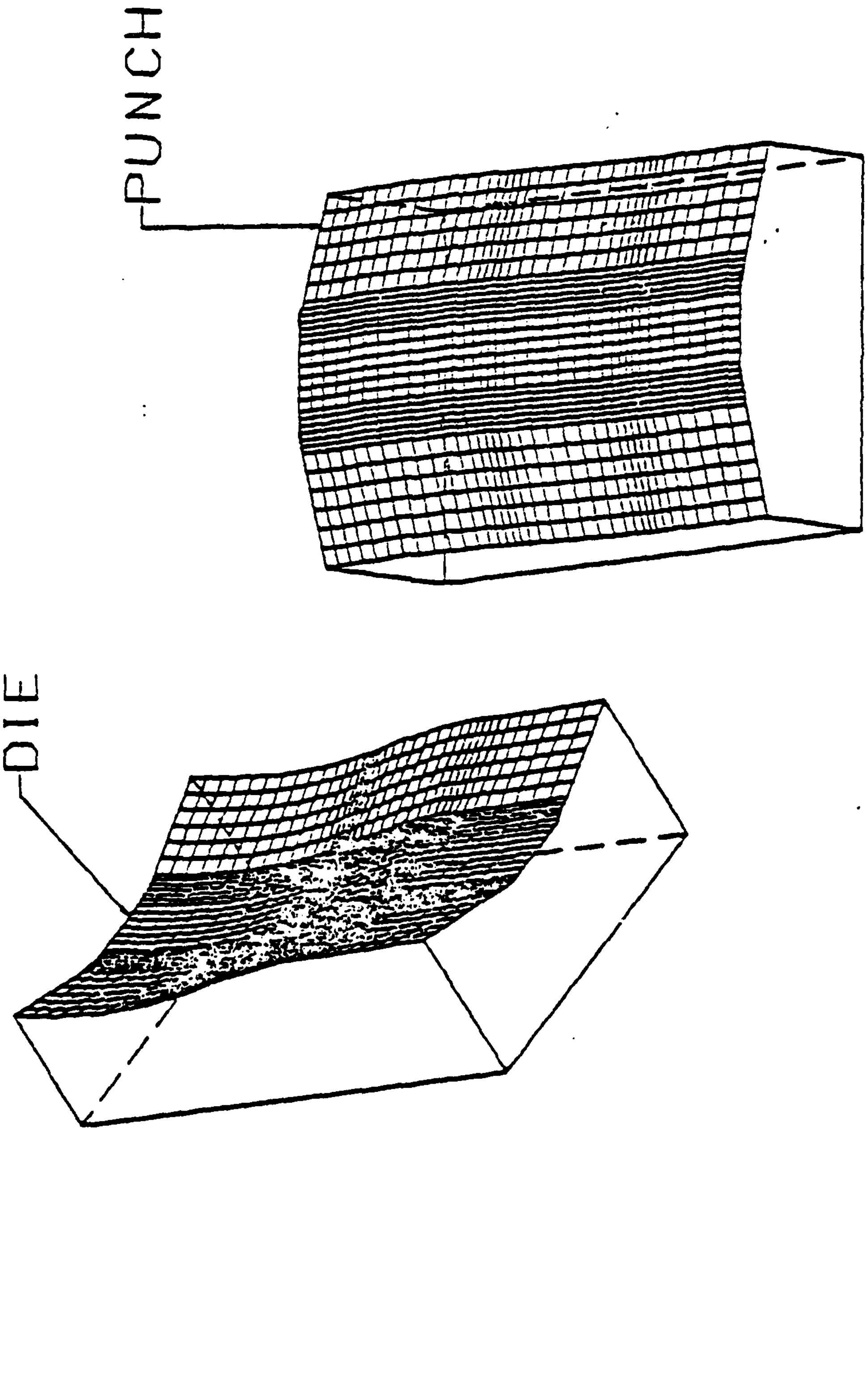

9.44
67.5335°
5.73
12.21
4.4805
1.5000R
3.36
LATHE
TEMPLATE
STG. 2 FAN DISK
F-404
MJH 3/20/78
4.54
3.22
CONTOUR TO BE WITHIN
.0005 GLASS LAYOUT NOXXXX


INSPECTION
LAYOUT
10 X STG. 1. FAN DISK
F404
LATHE TEMPLATE
T.D.NO. XXX
BY
MJH
3/20/78
HOR. DATUM LINE
MOVE
X 1.410
Y .982
MOVE
X .213
Y .830
MOVE
X 1.057
Y .640


1.987
.992
ENTRY POINT
VIEW 1
.409
.500 DIA. TOOLING BALL
.409
ELECTRODE
ENTRY POINT
.127
4.250
VIEW 5
VIEW 2

E.D.M. FIXTURE

FIGURE 14



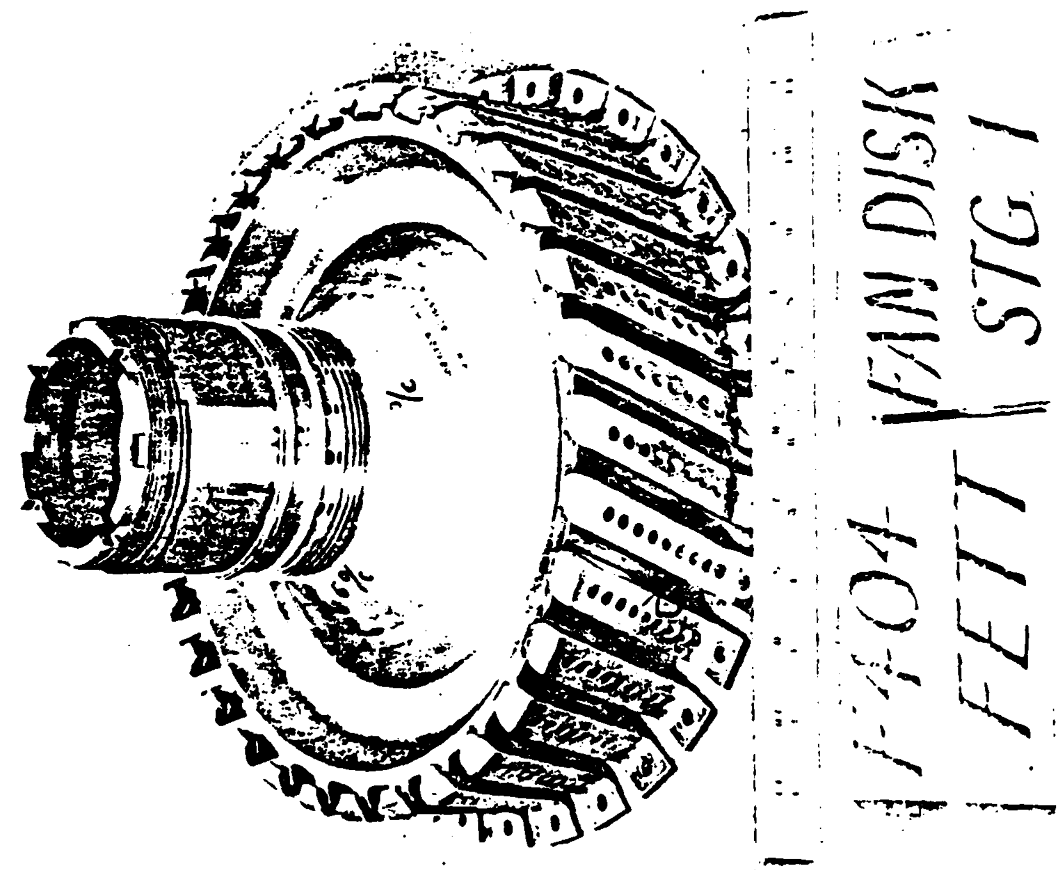
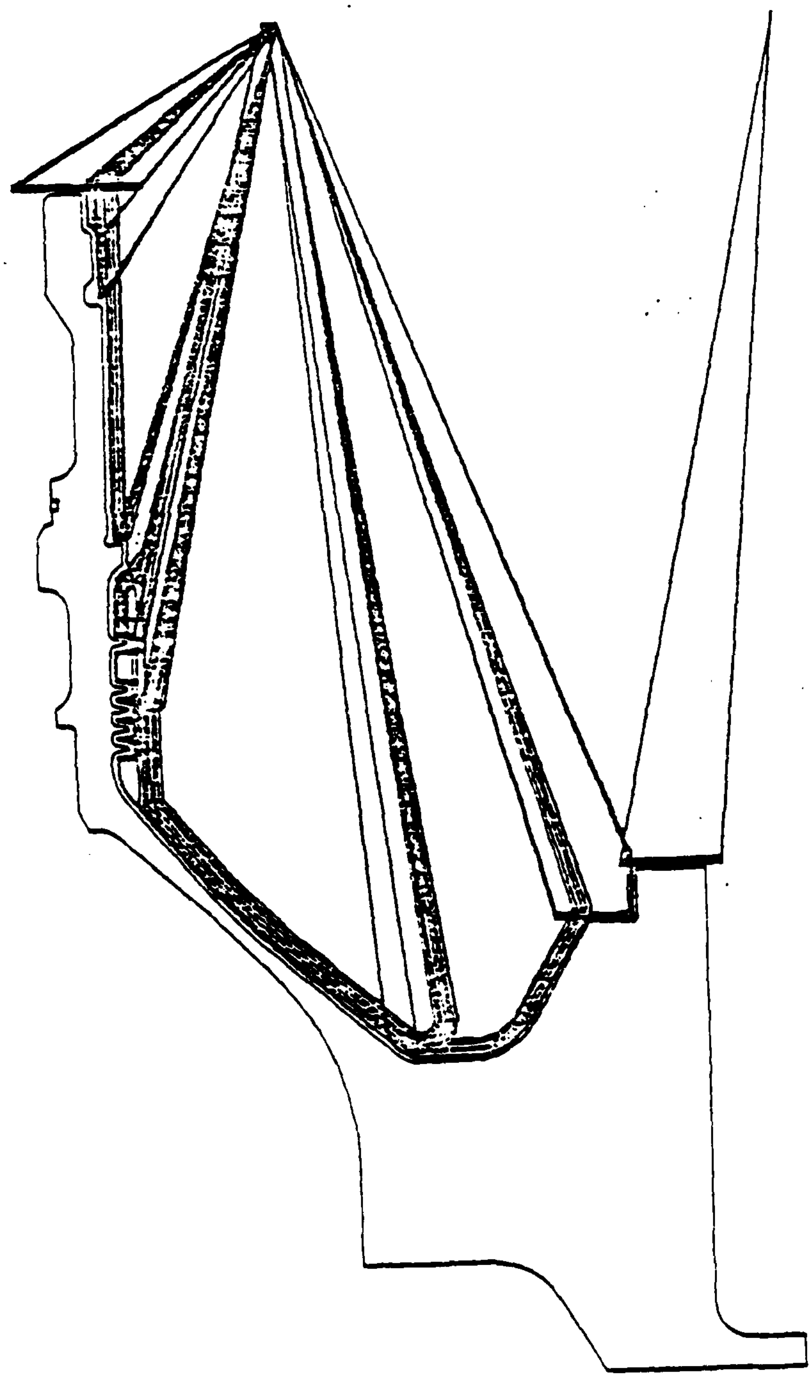

F404 FAN DISK
FETT STG 1

FIGURE 16



Report No. 1558

EXERCISING PROPULSION DTLCC METHODS ON ADVANCED DEVELOPMENT ENGINES

By: Eli H. Benstein
William Q. Wagner

Teledyne CAE
Toledo, Ohio

Engine Design and Life Cycle Cost Seminar,
Office of the Secretary of Defense (Sponsor)
17 - 19 May 1978,
Naval Air Development Center, Warminster, Pennsylvania

I (Continued)

A recent program at Teledyne CAE serves to illustrate the process. Component technology was directed at high performance, advanced development engines in the under-5,000 lb. thrust class, i.e. suitable for training and light attack aircraft. Therefore, an advanced trainer/light strike fighter, powered by an ATEGG-derivative turbofan engine, was selected as the application. The study plan (Figure 1) called for optimizing the engine design to achieve minimum engine and aircraft LCC.

Prior work at Teledyne CAE (Reference 3) involving an aircraft of about one third the gross takeoff weight (TOGW), suggested that aircraft weight is a first order measure of system LCC, hence should be a primary target in the LCC task. Accordingly, the study focused on the effect of engine design choices in the 1.5 - 5.0 range of bypass ratio (BPR) on the system, with a multi-billion dollar aircraft fleet as a target for LCC reduction.

II CHOICE OF THE BASELINE ENGINE

The primary selection criterion for a baseline* engine is: "best LCC performance of an ATEGG-derivative turbofan engine in a Trainer/Light Strike Fighter Aircraft".

In order to derive the "best" engine, the study encompassed:

1. Verification of the aircraft mission requirements;

2. Derivation of applicable turbofan engines for the selected mission, based on one core; analyses of their installed performances;

3. Layout, weight analysis and acquisition cost estimates of the engines;

4. Performance analysis of the engine/aircraft combinations with the mission fixed;

5. Computerized assembly of the incremental cost effects of the engine on the aircraft: gross weight, acquisition, maintenance, and fuel costs;

6. Presentation of life cycle costs as a function of bypass ratio.

---

* Later used for detail component LCC tradeoff analyses.

II (Continued)

AIRCRAFT MISSION REQUIREMENTS - Mission data were collected from airframers and current service views on a combined USAF/USN trainer/light strike fighter. This established the aircraft operational envelope of Figure 2 and the mission leg definitions of Figure 3.

APPLICABLE TURBOFAN ENGINES - Based on prior work, it was determined that applicable engine bypass ratios should range from approximately 1.6 to 5.0, thus should present data over the broadest range of engine design impact on LCC.

A set of turbofan engine designs was constructed around an ATEGG gas generator:

Engine Model No.	Bypass Ratio	No. of Fan Stages	No. of LP Turbine Stages
G-3	1.65	2	2
W-2	2.50	1	1
R-2	4.91	1	3

Maps were predicted for each version of the core engine, representing the gas generator compressor with stage stagger or design modifications and geometry schedule variations, to optimize performance with each fan match.

Once the core engine components were chosen (the high temperature turbine is common to all three engines, thus does not require optimization), a "mini optimization" was performed to choose the proper fan pressure ratio. An operating line was calculated for the HP spool, and fan pressure ratio varied to determine SFC/thrust tradeoffs for the cycle. It was known from prior work that the low level navigation mission leg (Column 3 of Figure 3) is the sizing criterion for the aircraft fuel load. At this condition, the aircraft operates at about 50-
-70 percent of available maximum thrust, hence the optimization was carried out at a representative value of 1,200 lb. thrust. The results indicated the choice of fan pressure ratios to match (at sea level and altitude) with each engine configuration.

Following selection of the three point-designs, final component maps were assembled on the computer, and performance models calculated for uninstalled and installed conditions over the flight spectrum. For installed conditions, aircraft service load and nacelle drag calculations were made.

PERFORMANCE ANALYSIS OF THE ENGINES - Figures 4 and 5 illustrates the losses involved in the nacelle installation, due to boat tail drag, spillage drag, and inlet pressure loss. They show the higher loss incurred by a high bypass

II (Continued)

ratio engine, especially at low altitudes and high flight speeds. The loss information is summarized in Figure 6, as lapse rate versus bypass ratio at a 4G turn condition. Because the 4G turn requirement at 15,000 ft. and Mach 0.7, sizes the engine, the differences in lapse rates shown on this figure have major impact on the engine and aircraft design. The high bypass R-2 configuration loses 16.5 percent of its performance due to installation effects; the lower bypass G3 system loses only 5.5 percent. When combined with the natural cycle thrust reduction due to bypass ratio, the installed R-2 engine produces, for a common gas generator, 22 percent less thrust than the G-3 at 15,000 ft., M = 0.7.

The performance of the three engines over the flight spectrum was then integrated (as scalable engines) into the aircraft design synthesis.

PERFORMANCE ANALYSIS OF THE AIRCRAFT/ENGINE COMBINATIONS - A baseline aircraft gross weight of 9,900 pounds was chosen, with a wing loading at 58 pounds per square foot, and a 2,970 pound fuel capacity. A typical aircraft configuration is shown in Figure 7. Figure 8 presents the flying efficiency of the trimmed baseline aircraft, with key mission points superimposed on the lift-drag curve.

For the simplified type of aircraft analysis used, the gross weight was subdivided into a fuel weight, a pilot weight, an equipment weight (common to the mission requirements), and a scalable structures weight. The latter number is a function of the propulsion system weight, the aircraft efficiency, and the amount of fuel, with its tankage, necessary to meet the mission range. In each case it was discovered that the low level navigation mission sized the aircraft fuel tankage, whereas the 4G turn requirement set the engine thrust level, hence its weight and its "leverage" on the aircraft gross weight. From a prior APSI study, an engine weight leverage factor (influence coefficient) of 3.0 pounds of aircraft weight per pound of engine weight was chosen.

Simplifying assumptions, consistent with the study scope were made: the engine performance is known to be scalable and its thrust/weight constant, over the limited size range; the aircraft aerodynamic (L/D) efficiency was assumed constant over the installations required by the varying bypass ratio. The method of aircraft calculation, i.e. by impacting only the nacelle-installed engine performance with the effects of bypass ratio, assumes a clean fuselage and wing design.

To develop the detailed aircraft characteristics, an iteration procedure was established for the 4G turn requirement, using the constant and scalable factors described above. The installed thrust for each engine was scaled until a match occurred between installed thrust required for the 4G turn and the aircraft gross weight resulting from the engine size. This defined basic engine/airframe characteristics, engine scale factor required to meet the 4G turn, and the resulting fuel capacity of the aircraft.

II (Continued)

Each aircraft was then run through the low level navigation mission to ensure that sufficient fuel was onboard to meet the range requirements. It was found that the sizing procedure resulted in sufficient fuel to meet the mission requirement with reserves.

The aircraft performance was then checked at a few points around the operating envelope to ensure that no other desirable mission characteristics were violated by the procedure. For example, a maximum Mach number of 0.83 was calculated, as is typical of current similar systems.

The data required for the subsequent Life Cycle Cost inputs are summarized in Figure 9, while the summary curve of Figure 10 indicates that the lowest gross weight aircraft is obtained by a bypass ratio between 1.0 and 1.6. The analysis is not sufficiently accurate to pinpoint an exact value within this range; it does clearly identify the main "optimum" engine characteristics.

Increasing bypass ratio was found to yield an increasingly heavy aircraft and a larger scale factor for each engine - typically the 2.5 bypass ratio W-2 configuration must be scaled from its baseline thrust of 2,520 pounds by a 1.176 factor to 2,965 pounds thrust to meet the 4G turn requirement. The 4.9 bypass ratio R-2 configuration requires a 1.53 scale factor, from 3,200 to 4,900 pounds thrust. The high bypass ratio engine also limits maximum achievable Mach number to values below 0.79 at altitude and inhibits the Mach number which can be achieved at sea level.

III LCC ANALYSIS

During and following the baseline engine selection task, an LCC analysis was conducted to:

1. Accept (or reject for additional design work) the hypothesis - that the lowest TOGW aircraft represents the lowest LCC design.

2. Insure that all significant engine/aircraft LCC elements were considered.

3. Provide LCC sensitivity relationships for following tasks of the component program.

LCC METHODOLOGY - The analytic approach used Teledyne CAE's APSICOST methodology, which includes computerized routines which identify major LCC elements and hierarchial subsets (Figure 11) of an aircraft engine life cycles; i.e.:

1. Development
2. Acquisition
3. Operation and Support (including fuel)
4. Interactive (engine impact on airframe LCC).

III (Continued)

The model is also intended to mesh with the traditional process of propulsion engine design (Figure 12), hence fits this problem statement well.

TRAINER/LSF SYSTEM DEFINITION - The definition task started with synthesis of a training mission (Figure 3) and a requirement for 900 aircraft (during the fleet's "steady-state" years). Each would fly 370 missions, or 830 hours per year of service. The aircraft fleet was then varied (+/-300 aircraft), while holding a constant sortie requirement, to test the individual aircraft's lifetime utilization consequence. (Figure 13).

LCC DATA BASE - A baseline LCC analysis was developed for each of the three engine/airframe configurations:

1. Engine Development Cost was principally determined from Reference 4, using engine parameters which include Mach No., Quantity and Model Qualification Date (MQT). (These results are deterministically assessed in subsequent phases of the component program).

2. Engine Acquisition Costs were estimated from Teledyne CAE's deterministic engine acquisition cost routines which provide guidelines to engineering and processing personnel during advanced/exploratory development.

3. Airframe Development & Acquisition costs were estimated from the regression-derived coefficients and the methods of Reference 5.

4. Aircraft/Engine Operation & Support Costs were derived from the mission analysis for fuel cost and consumption per sortie; from the maintenance estimating relationship of Reference 6, for man hours per flight hour; and from Teledyne CAE's data banks, for the balance.

The LCC data, as typified in Figures 14 and 15 was then input to, and executed in the APSICOST engine-DTLCC, methodology. During that process all cost input/output was adjusted to 1979 constant-year dollars ($'79).

LCC RESULTS - An LCC consequence for each engine design was developed. It included most of the 100+ elements of Reference 7, as typified by the summary of major categories in Figure 16 and the overall comparison of Figure 17. In this instance, the lowest life cycle cost engine and system was obtained for the 1.65 BPR, G-3 engine design.

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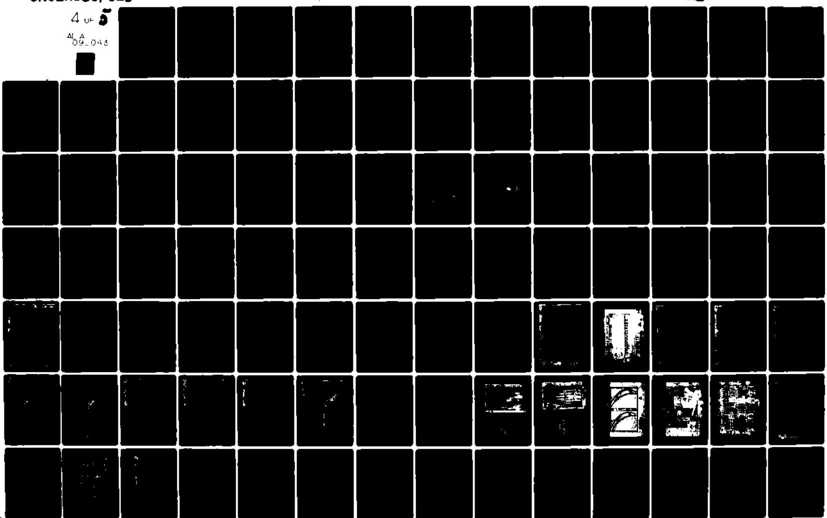

IV CONCLUSION

The Trainer/Light Strike Fighter study typifies the complex but significant way in which engine and airframe designs react with mission requirements to produce life cycle cost consequences.

It is concluded that engines in the bypass ratio range 1.0 - 1.65 offer the lowest LCC in a fixed mission, high performance trainer/light strike fighter application. The LCC savings can be as much as $1.5 billion for a 900 aircraft fleet as compared to the choice of a high bypass ratio engine.

It is also understood that pinpointing a "best" engine requires a more detailed, and especially a more integrated engine/airframe trade study; i.e. with competent aircraft manufacturer design support, focusing on the narrowed bypass ratio range.

Such a detailed study would also encompass trading off the 4G turn requirement and Low Level Navigation range to test their LCC worth. These qualifications apply primarily to a final system concept validation study. The analysis described in this paper served its purpose well, by providing an engine/aircraft LCC baseline for measuring the worth of advanced technology engine component candidates. An indication of the subject's complexity and its unanswered questions is intended to stimulate additional engine community interest in DTLCC - which result would make the analysis additionally worthwhile.

ACKNOWLEDGEMENTS

The authors are obliged to Teledyne CAE management and Mr. Wes Knight, Project Engineer, APSI for active support of this effort; to Messrs. Bob Anderson and Dave Wiltse at Teledyne CAE, for contributions thereto; and to AF/APL, as represented by Messrs. Mike Barga and Bob Panella, for continued sponsorship and encouragement.

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6. Gregor, D.; Pates, P.; Harman, D.; "Maintainability Estimating Relationship", Proceedings, 1975 Annual Reliability and Maintainability Symposium, 75RM004.

7. Air Force/Industry Life Cycle Cost Working Group, "Turbine Engine Life Cycle Cost Model", ASD/YZ, letter dated February 1977.

CAPTIONS FOR ART

Figure No.	
1	Study Plan to Select Lowest LCC Engine Design
2	Operational Envelope of the Trainer/Light Strike Fighter
3	Missions Required of the Trainer/Light Strike Fighter
4 & 5	Boat-Tail and Spillage Drag Reduce High Bypass Ratio Engine Performance More Than Low Bypass Ratio
6	Lapse Rate and Installation Losses of the High Bypass Engine Combine to Degrade Performance
7	Typical Trainer/Light Strike Fighter Configuration
8	Flight Performance of the Baseline Aircraft
9	Summary of LCC Input Data
10	Effect of Bypass Ratio on Gross Takeoff Weight of a Trainer/Light Strike Fighter
11	"APSICOST" Propulsion Engine DTLCC Program
12	"APSICOST" Integration in Propulsion Engine Design Process
13	Trainer/Light Strike Fighter Utilization Versus Aircraft Fleet Size
14	Typical LCC Input, Airframe Data, W-2 Configuration
15	Maintenance Man Hours/Flight Hour (MMH/FH) Comparisons for Three Configurations
16	Typical Summary of Major LCC Elements, W-2 Configuration
17	Effect of Bypass Ratio on LCC of an Advanced Technology Trainer/Light Strike Fighter

Teledyne CAE
Report No. 1558

EXERCISING PROPULSION DTLCC METHODS ON ADVANCED DEVELOPMENT ENGINES *

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William Q. Wagner ***
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Toledo, Ohio

ABSTRACT

This paper describes one engine manufacturer's exercise of design to life cycle cost (DTLCC) methodology during the advanced development phase of an aircraft gas turbine engine. The method identifies a prospective aircraft application for the engine family; the aircraft baseline configuration and performance characteristics; its sizing mission and multi-mission requirements. Subsequently, a range of engine configuration changes is examined for life cycle cost impact on both the engine and the airframe, holding payload and mission performance requirements constant.

This example examines a military trainer/light strike fighter aircraft as a candidate application for an advanced development, non-afterburning, turbofan engine. The engine configurations scale from a common core, a common technology base, and a common manufacturing base. They differ principally in bypass ratio and size.

The LCC optimization process is facilitated by a computerized model that distinguishes the various airframe and engine-related LCC elements including development, acquisition, support and fuel.

It is shown that aircraft gross takeoff weight and system life cycle cost are reduced (in this study) by 33 and 21 percent respectively when the best engine bypass ratio is selected.

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* Research was sponsored in part by the USAF Aero Propulsion Laboratory, Contract No. F33657-77-C-0424

** Director, Engineering

*** Manager, Advanced Development Applications

I INTRODUCTION

The costs of developing, acquiring and operating military aircraft are increasing at significant rates. Therefore, DOD is placing more emphasis on the life cycle cost (LCC) consequences of weapon system design and development. In this regard, aircraft propulsion systems pose a particularly important and formidable LCC challenge because:

Gas turbine engines are costly to acquire and maintain;

Engine RDT&E involve the state-of-the-art of material, performance, structural, design, industrial and system sciences;

Propulsion engines profoundly interact with, "size" and "drive" aircraft weapon system cost. (Reference 1)

Teledyne CAE has been responding to the engine cost reduction challenge in a series of advanced development efforts including the Aircraft Propulsion Subsystem Integration (APSI) and the Advanced Turbine Engine Gas Generator (ATEGG) programs. These include a methodological evolution which Teledyne CAE identifies as design-to-life-cycle cost (DTLCC), specifically aimed at optimizing the cost-durability-performance balance of gas turbine propulsion engines. The work was accomplished in mutually supportive projects, i.e.:

APSI programs sponsored development of DTLCC methodology, including a set of computerized routines known as "APSICOST"* (Reference 2)

ATEGG programs utilized the methodology to select, assess and demonstrate engine and component candidates.

An important task of advanced development is to outline the 5-10 year distant application of the technology being evaluated as precisely as necessary to support tradeoffs and lead to design choices, and yet with an awareness of the imprecision or uncertainty of such a distant event.

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* Aircraft Propulsion Subsystem Integrated Cost of Ownership with System Tradeoffs.

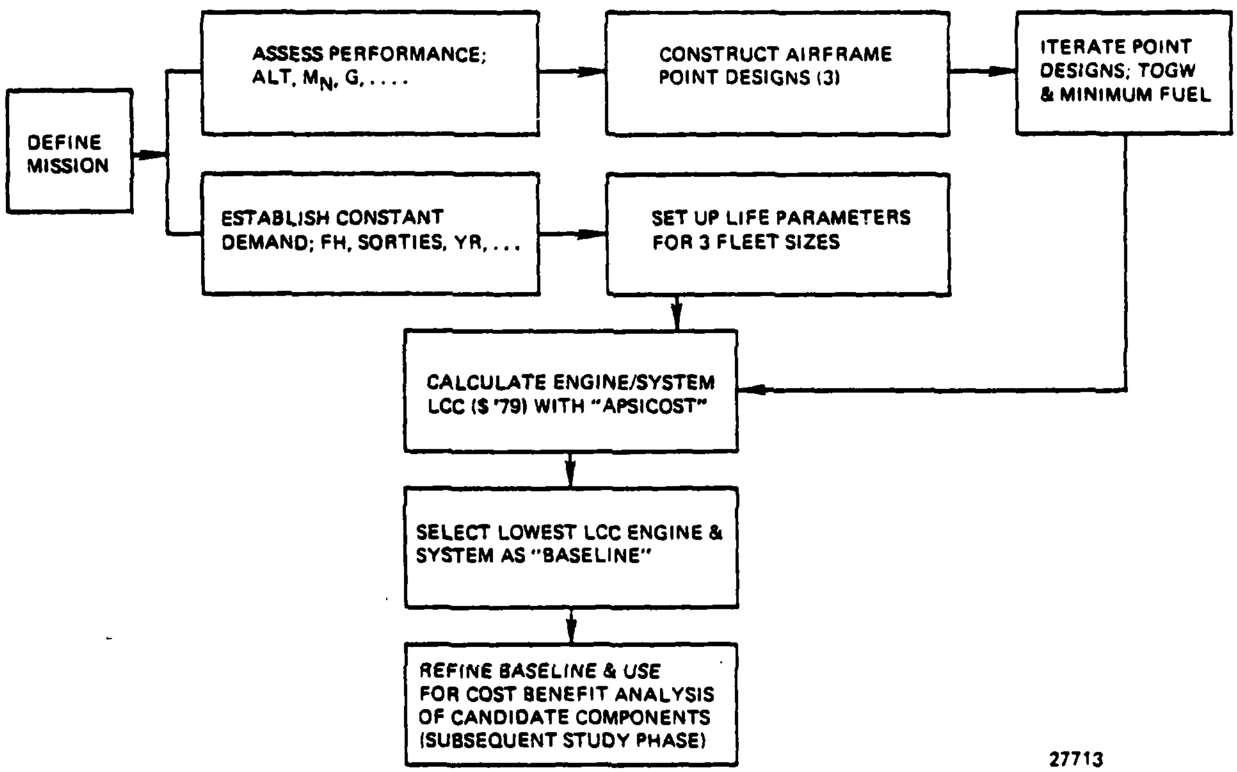


Figure 1. Study Plan to Select Lowest LCC Engine Design.

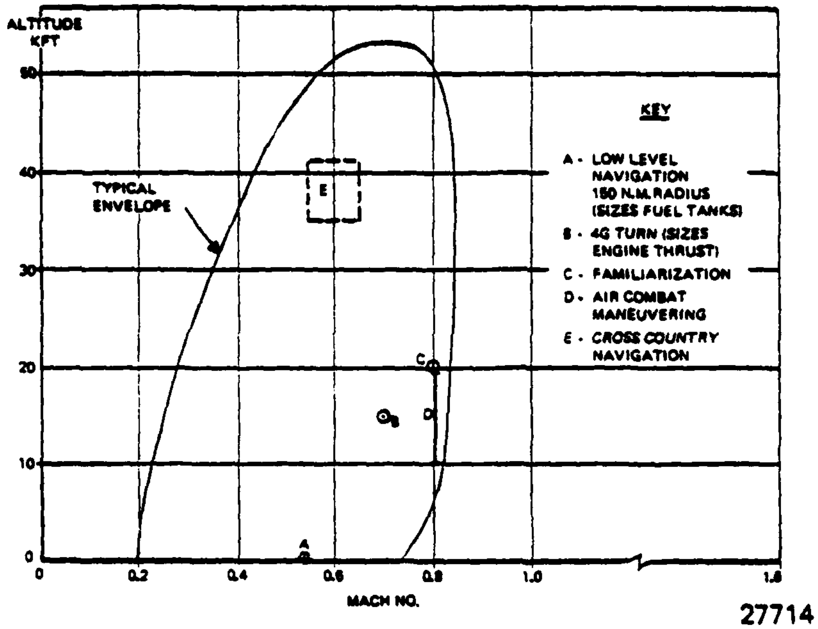


Figure 2. Operational Envelope of the Trainer/Light Strike Fighter.

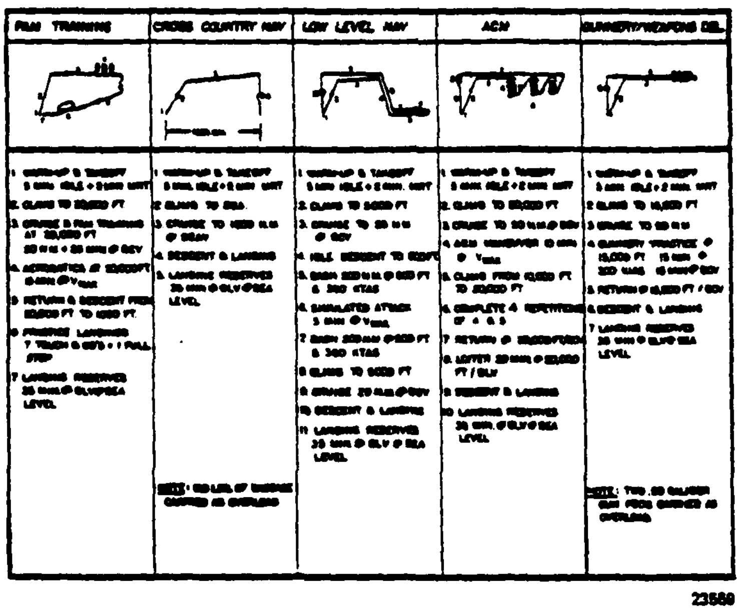
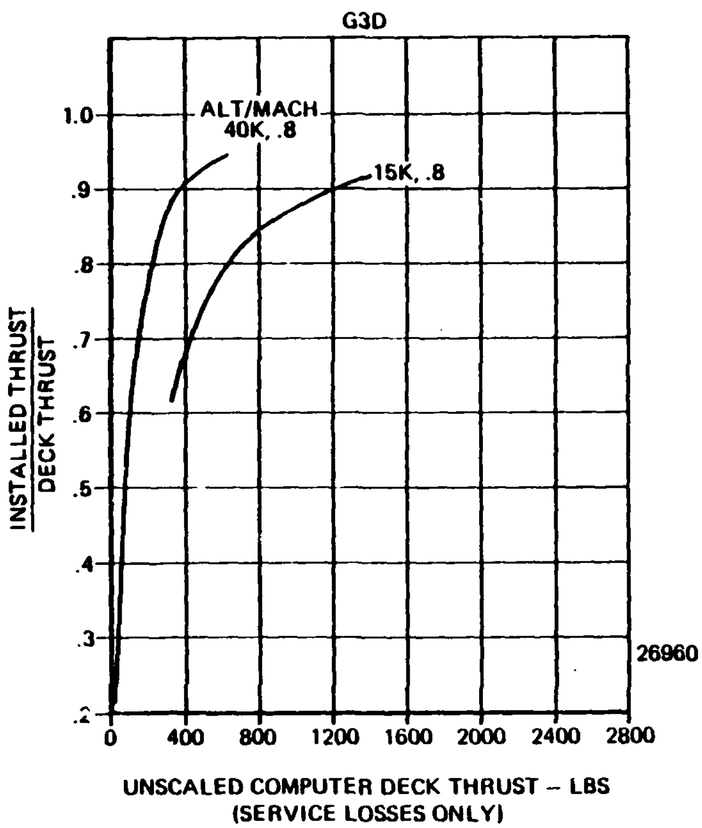
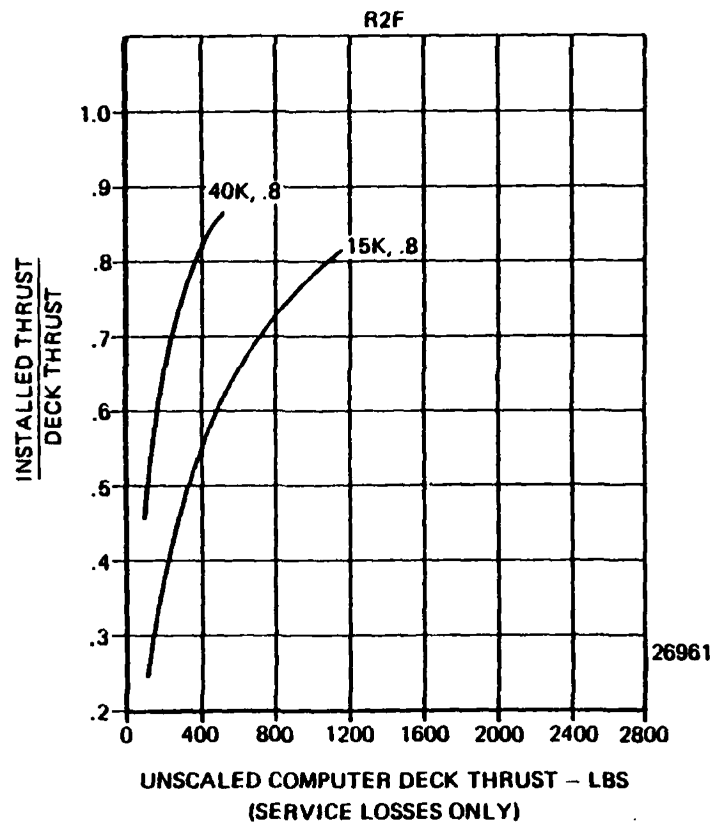


Figure 3. Missions Required of the Trainer/Light Strike Fighter.





Figures 4 (Left) and 5 (Right). Boat-Tail and Spillage Drag Reduce High Bypass Engine Performance More Than Low Bypass Ratio.

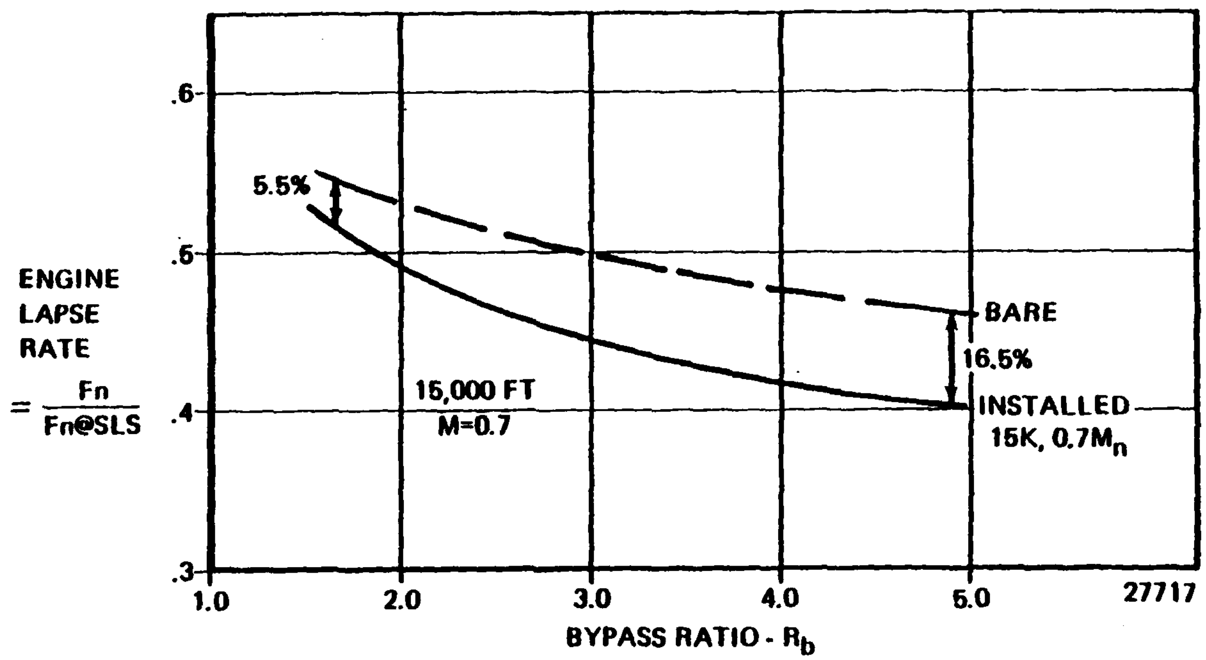


Figure 6. Lapse Rate and Installation Losses of the High Bypass Engine Combine to Degrade Performance.

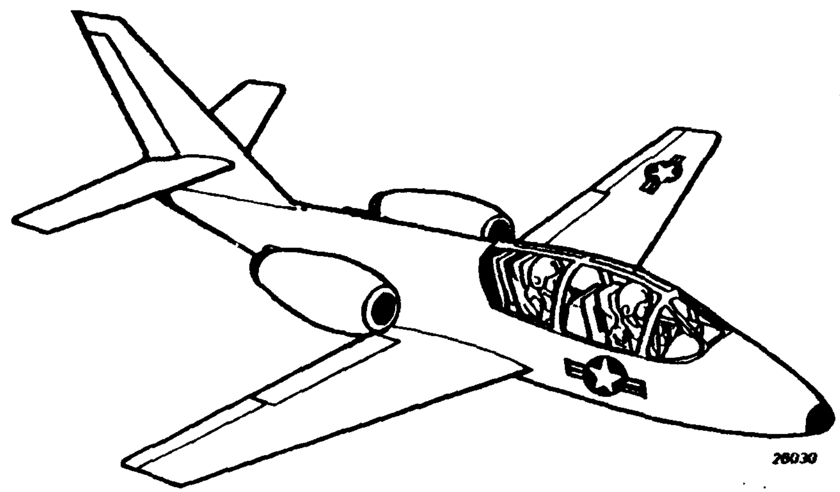


Figure 7. Typical Trainer/Light Strike Fighter Configuration.

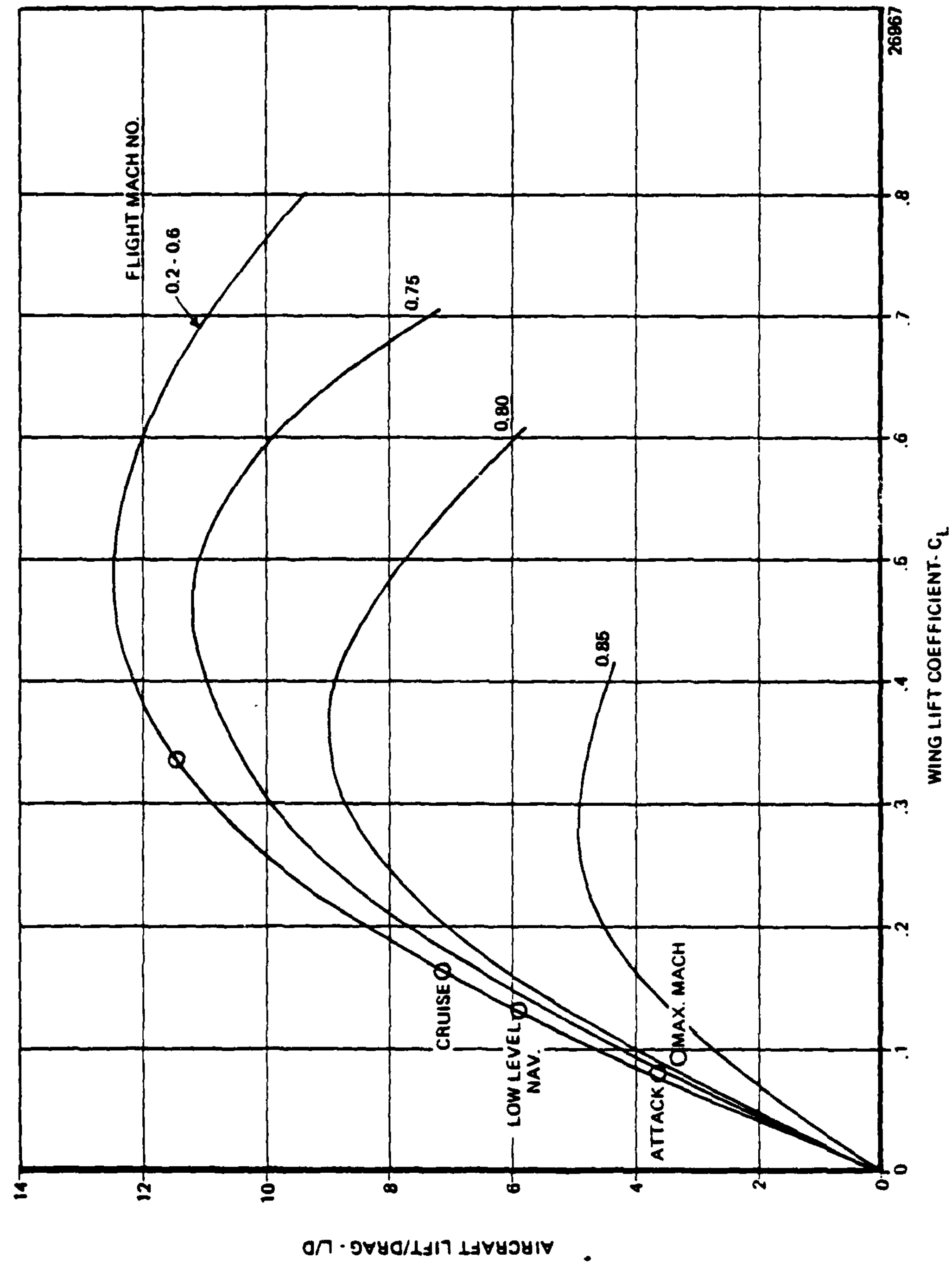


Figure 8. Flight Performance of the Baseline Aircraft.

ENGINE MODEL	G-3	W-2	R-2
Base Thrust	2840	2520	3200
Bypass Ratio	1.65	2.5	4.9
Thrust/Wt. Ratio	5.43	5.40	5.20
Scale Factor In Derived Aircraft	1.000	1.176	1.530
Thrust in Aircraft (1 Eng.)	2840	2965	4900
Eng. Wt. in Aircraft (1 Eng.)	523	549	942
Aircraft SLS Thrust Loading	0.580	0.571	0.671
Aircraft Gross Wt.	9679	10124	14428
Fuel Wt. - Useable and Unuseable (31)	2801	3041	4262
Pilot Weight (2) & gear	502	502	502
Equipment Weight	2354	2354	2354
(Scalable) Structures Wt.	2938	3091	5388
Oil Weight	38	38	38
Max. Mach @ S.L.	0.782	0.778	0.745
Max. Mach @ 40K Ft.	~0.87	~0.84	~0.79

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Figure 9. *Summary of LCC Input Data.*

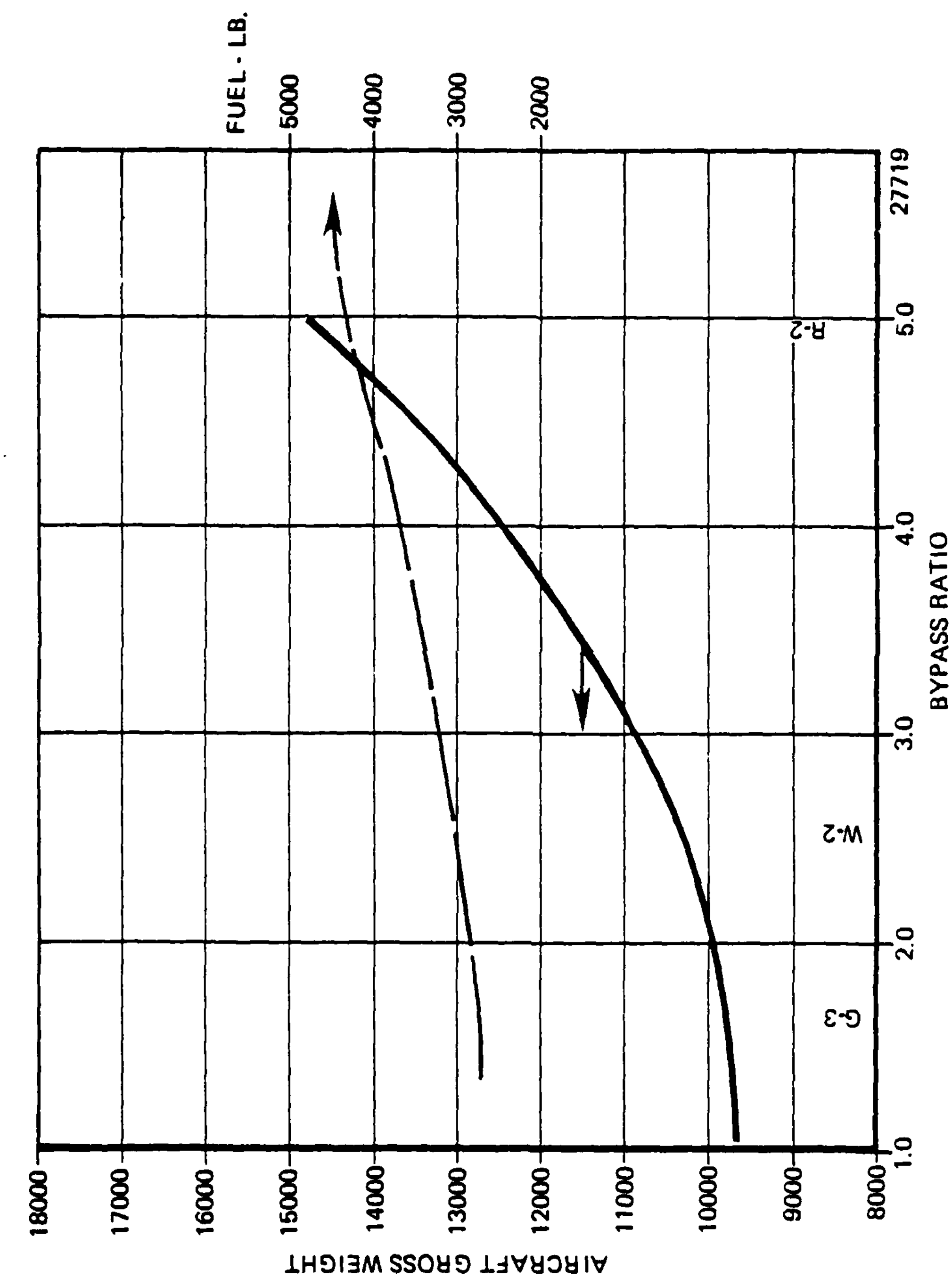

Figure 10. Effect of Bypass Ratio on Gross Takeoff Weight of a Trainer/Light Strike Fighter.

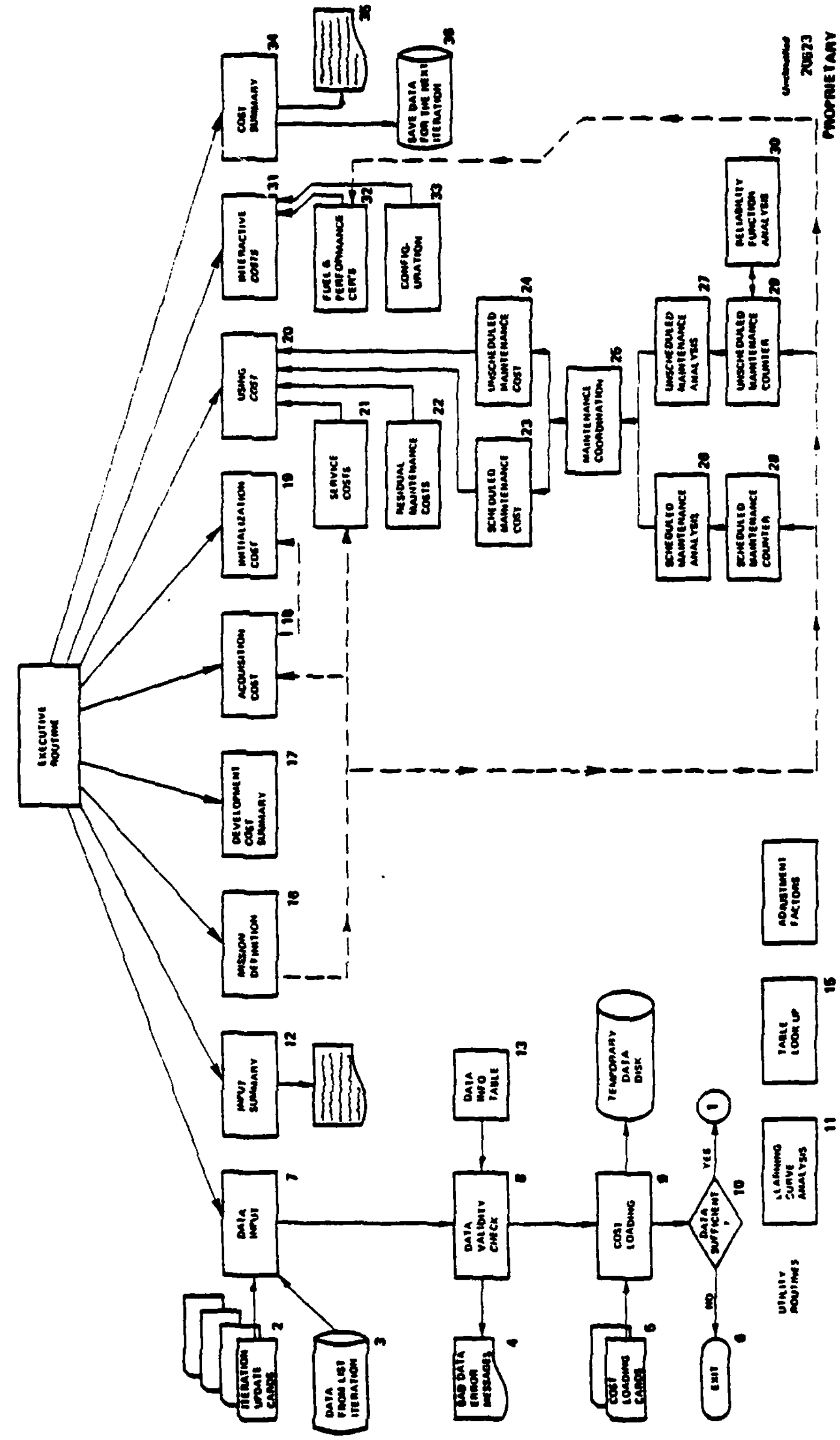

Figure 11. "APSICOST" Propulsion Engine DTLCC Program.

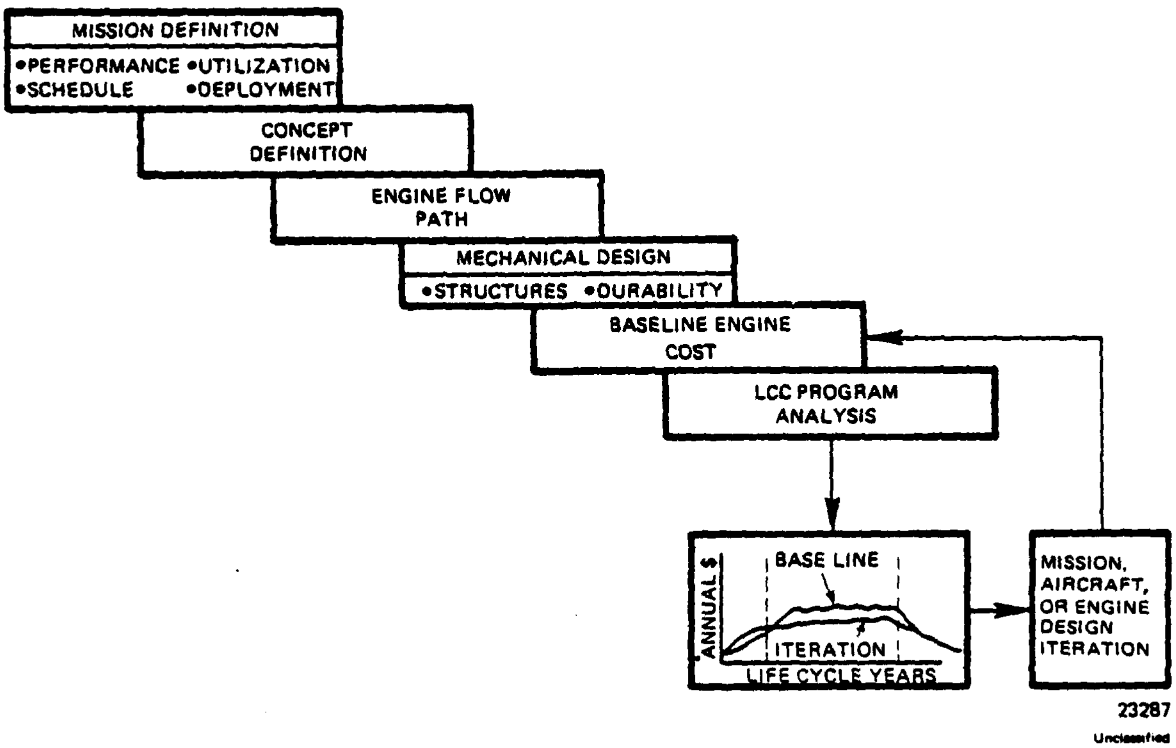

Figure 12. "APSICOST" Integration in Propulsion Engine Design Process.

UTILIZATION BASELINE PARAMETERS

FLYING DAYS/MONTH	20
SORTIES/DAY	2
SORTIES/YEAR/AIRCRAFT	480
MISSIONS/YEAR/FLEET	336,000

MISSION BREAKDOWN

MISSION	%	MISSIONS/YR/FLEET	HRS/YR/FLEET
FAMILIARIZATION	25	84,000	168,000
CROSS COUNTRY NAVIGATION	30	100,800	371,000
LOW LEVEL NAVIGATION	25	84,000	104,000
AIR COMBAT	10	33,600	67,200
GUNNERY WEAPONS	10	33,600	37,300
TOTALS	100	336,000	747,600

FLEET SIZE BREAKDOWN

PARAMETER	700 A/C	900 A/C	1200 A/C
MISSIONS/YR/AIRCRAFT	480	370	280
HOURS/YR/AIRCRAFT	1070	830	620
HOURS/LIFE/AIRCRAFT	21,400	16,600	12,500

26890

Figure 13. Trainer/Light Strike Fighter Utilization Versus Aircraft Fleet Size.

AIRFRAME DEVELOPMENT* X 10^6 ($ '79)

COST ITEM	COST
ENGINEERING	38.8
TOOLING	23.4
NONRECURRING MANF. LAB.	5.5
RECURRING MANF. LAB.	30.0
NONRECURRING MATERIALS	1.5
RECURRING MATERIALS	5.5
FLIGHT TEST	4.5
QUALITY CONTROL	4.6
TOTAL	113.8

* USING 30 DEVELOPMENT AIRFRAMES AND 4 FLIGHT TEST AIRCRAFT

AIRFRAME ACQUISITION* X 10^6 ($ '79)

COST ITEM	700 A/C	900 A/C	1200 A/C
ENGINEERING	14.1	15.5	17.2
TOOLING	44.0	46.8	51.9
RECURRING MANF. LAB.	178.0	214.6	265.0
RECURRING MATERIAL	84.3	105.6	136.4
QUALITY CONTROL	24.9	30.0	39.0
TOTAL	345.3	412.5	507.5
UNIT COST	0.493	0.458	0.423

26887

* LESS ENGINES AND OTHER GFE.

Figure 14. Typical LCC Input, Airframe Data, W-2 Configuration.

	ENGINE AIRFRAME CONFIGURATION		
MODEL	G-3	W-2	R-2
ENGINE BPR	1.65	2.50	4.90
AIRCRAFT Fn(TOTAL)	4960	5930	9800
AIRCRAFT GTOW, LB	9629	10124	14428
MMH/FH (PROPULSION)	0.75	0.75	0.84
MMH/FH (BALANCE)	6.24	6.30	7.06
MMH/FH TOTAL	6.99	7.05	7.90

27720

Figure 15. Maintenance Man Hours/Flight Hour (MMH/FH) Comparisons For Three Configurations.

LCC SUMMARY, W-2 CONFIGURATION			
LCC Item	700 A/C Fleet	900 A/C Fleet	1200 A/C Fleet
Airframe Development	113,771	113,771	113,771
Airframe Acquisition	345,282	412,508	507,566
A/C Organization	703,562	701,680	698,886
A/C Intermediate	358,500	357,545	356,104
Inspection	1,568,327	1,564,125	1,557,863
Engine Costs	2,404,463	2,480,571	2,593,904
Attrition	112,760	108,046	103,271
Total	5,606,665	5,738,246	5,931,365

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Figure 16. Typical Summary of Major LCC Elements, W-2 Configuration.

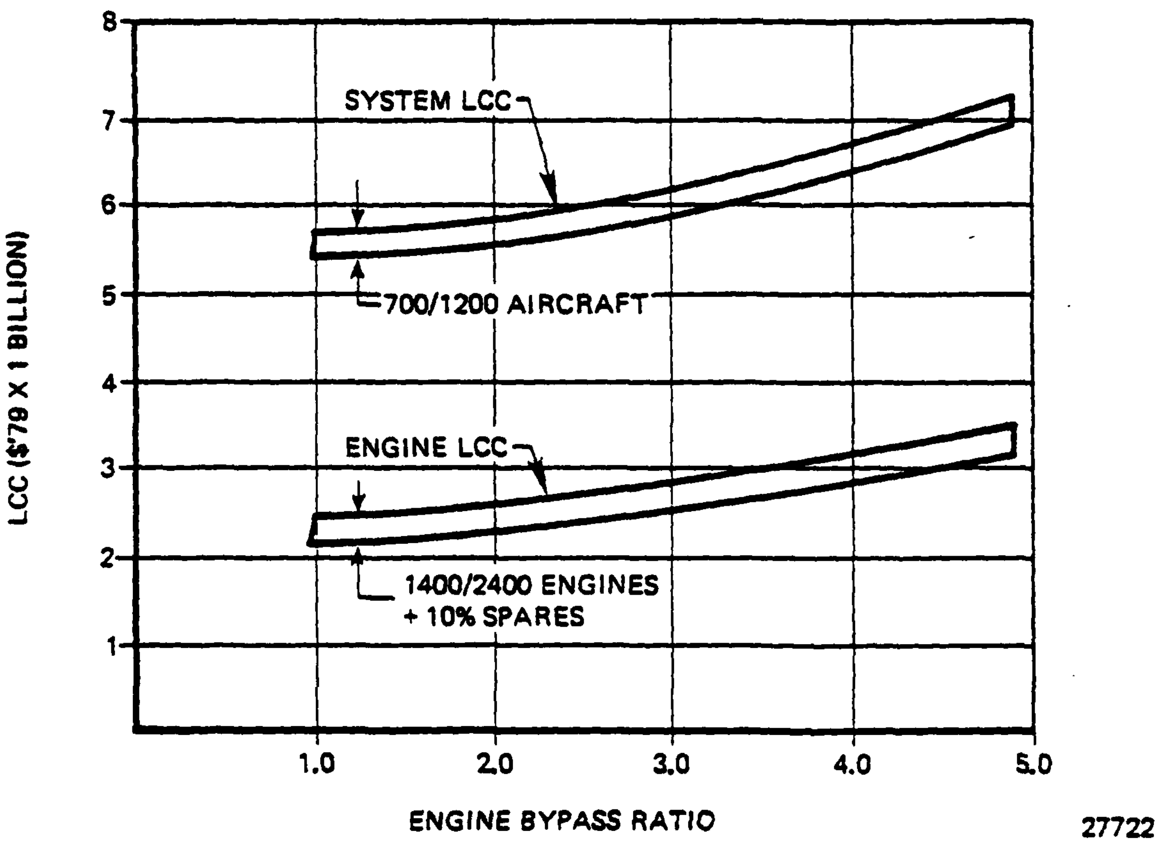

Figure 17. Effect of Bypass Ratio on LCC of an Advanced Technology Trainer/Light Strike Fighter.

LIFE CYCLE COST CONTROL

By

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INTRODUCTION

"By the start of Full Scale Development (FSD), 90% of an engine's Life Cycle Cost is fixed." We are all familiar with this or similar statements. I believe, however, that it needs some modification. It is quite probable that 90% of the minimum attainable LCC is established, but, without proper control throughout the ensuing phases of the engine life cycle, total costs can mushroom beyond recognition. I intend to address here some of the practices used at the Aircraft Engine Group of General Electric to control engine LCC during the various life cycle phases. I had originally titled this paper "LCC Control - Conception to Retirement." This was overly ambitious; we haven't retired an engine from service since the advent of LCC as a discipline, so I will restrict this dissertation to LCC control into the Operation and Support phase and will explain that control of engine LCC requires that

a) the individual design engineer have the necessary tradeoff tools available,

b) meaningful, measurable requirements for LCC drivers be established,

c) methods of tracking those cost drivers subject to growth during the life cycle be established,

d) appropriate incentives are provided to meet or better LCC driver requirements,

e) the customer utilize the full LCC potential in operating the engine.

I do not intent to explain or justify our methodology of modelling and estimating the baseline Life Cycle Costs. LCC modelling is such an extensive subject that it could provide the basis for a series of papers, or be the subject of a seminar in itself.

The material I will use in this presentation is particularly representative of two engine programs - the T700 and F404, two engine designs which have developed concurrently with the increasing emphasis on LCC. It is significant, I believe, that both programs were preceded by demonstrator or prototype programs. In the case of the T700, it was the GE12 demonstrator program, and, for the F404, the YJ101. Both programs provided a baseline from which meaningful standards or requirements could be established for LCC drivers.

In the case of the T700, LCC, as such, was not a spec however, Army planners had stated that the "reduction of ma: logistics support requirements was the major technical goal fc and further identified the primary risk associated with UTTAS of maintainability goals. As a result of this emphasis and m: between GE and the Army, a well prepared RFQ, contract, ar full scale development program have resulted in an engine wit maintainability, durability, and reliability -- three primary LC and low LCC.

Similarly, the F404 RFQ emphasized the priorities to be drivers, unit cost, reliability, and maintainability. Again, ex and discussions prior to contract award ensured that the FSD with a comprehensive list of LCC driver requirements that we strated and tracked right through to operational service. For an actual in-service parts usage rate ($/EFH) was listed as a was to be measured under operational conditions. Furthermore of these requirements carried significant incentives/penalties.

I refer to this in an attempt to illustrate the need for cor LCC by both customer and contractor prior to the start of FSD that, for maximum effect, this commitment must be enthusiasti throughout the engine's life span.

CONCEPTUAL DESIGN PHASE

LCC control commences concurrent with the start of preli. Initial studies will optimize the engine for the envisaged system the initial LCC profile will be established. This profile will ide of the costs associated with each of the LCC phases, the total c engine hardware, and fuel usage costs. The costs at this stage using parametric models which are based on GE experience in th engine design, development, manufacture and operation over the We have a high level of confidence in these models when applied

LCC Sensitivity to Weight, DTC Goal, and SFC

1% Δ	% Δ for Equivalent LCC Effect					
	Dash	Loiter	Attack	Overall	Engine Weight	DTC Goal
SFC Dash	1.0	2.84	5.61	.64	1.67	1.44
Loiter	.35	1.0	1.98	.22	.59	.51
Attack	.18	.51	1.0	.11	.3	.26
Overall	1.57	4.46	8.82	1.0	2.63	2.26
DTC Goal	.91	2.6	5.0	.57	2.4	1.3
Engine Weight	.6	1.7	3.35	.38	1.0	.87

Table 1.0

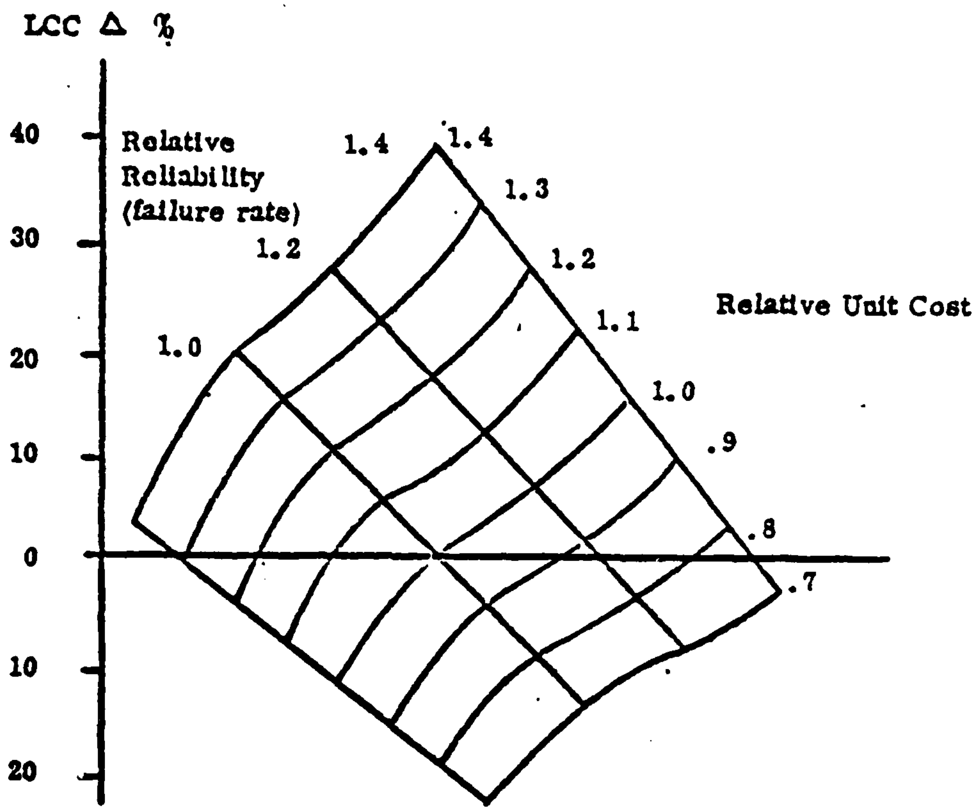


FIGURE 1 LCC Sensitivity To Reliability and Unit Cost

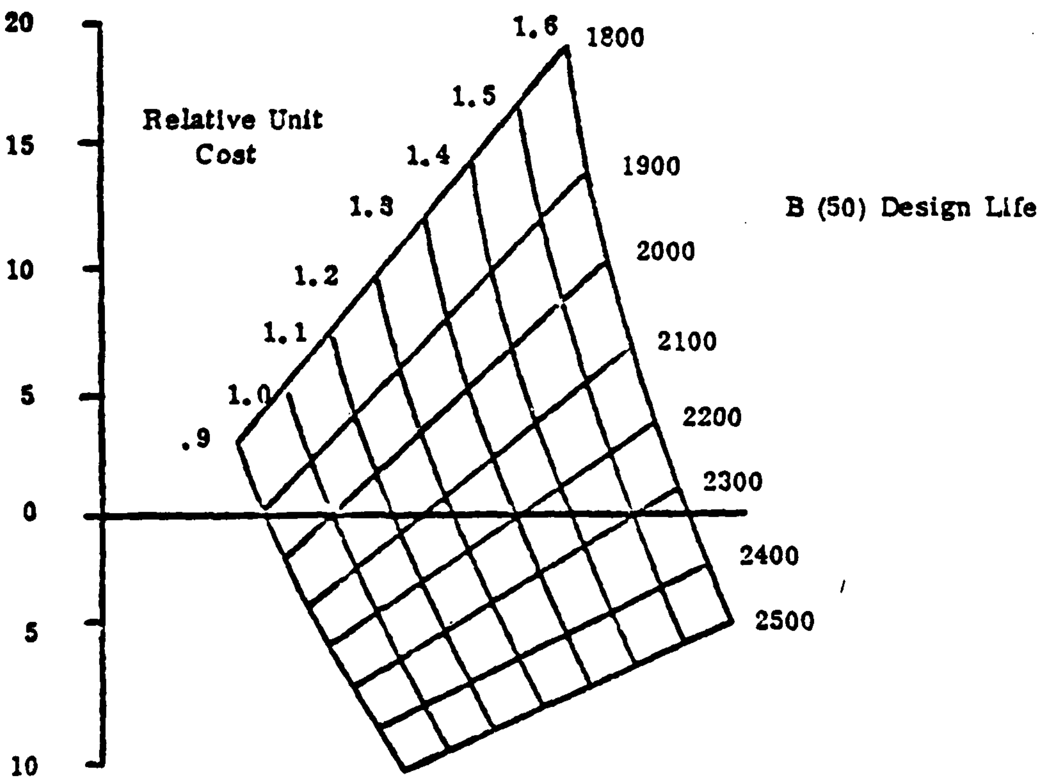


FIGURE 2 Engine Sensitivity to Durability and Unit Cost

Starting from this baseline configuration, the models are exercised to provide tradeoff relationships between the various system LCC drivers. During the conceptual phase, both engine and airframe are considered to be rubberized so that the effect on total system LCC may be considered. Typically, the acquisition cost effects of the airframe weight changes and fuel usage are the major non-engine costs considered.

The result of these trade studies provides the Preliminary Design Manager with a tool for evaluating alternate engine or component configurations. The form in which these tradeoff relationships are presented may be tabular, as in Table 1, or graphical, as in Figures 1 and 2.

It is important that prior to establishing these relationships, a firm understanding of the expected fleet size and operating scenario is established. Durability cost impact, for instance, is very much a function of the utilization that may be expected and the duration of the program. Utilization in this context is not to be considered solely in hours of engine operation but must consider the severity of this usage in terms of time at temperature and throttle cycles. Fortunately, this area has been subjected to considerable investigation by all branches of the military and we have a far better understanding of how an engine is really utilized. During this phase, the use of the carpet plots for durability and reliability are particularly useful; the LCC relationships are not usually linear and, at this stage of the design, large perturbations - particularly in durability - may be considered. The term "durability" is considered here to apply to components subject to wearout characteristics such as Low Cycle Fatigue (LCF) or Stress Rupture (SR) during the expected life span of the program. Cost effects are calculated using a model that simulates fleet aging and component wearout characteristics based on Weibull or log-normal distributions. The level of analysis and control at this stage is at the engine and major component level.

The use of these tradeoff relationships provides the basis for a conceptual engine study that will provide an optimum system level LCC.

FULL SCALE DEVELOPMENT (FSD)

This phase, which involves the detailed design and development of the engine, will fix the LCC capabilities of the engine. During this phase, control is of paramount importance. It is necessary that the contractor have not only the tools to evaluate the LCC impact of numerous component design alternatives that will result from the iterative nature of engine design and development, but also the management structure that provides accountability and decision authority. Finally, to be really effective, there must be firm, unambiguous requirements upon which an incentive/penalty structure can be equitably based.

In establishing tradeoff factors for the use of the design engineer during this phase, the concept of a rubberized vehicle and engine is replaced with a fixed vehicle and the established engine specifications. The LCC parameters considered by the designer in establishing his design are manufacturing cost, durability, reliability, and maintainability. In specific cases where engine design alternatives impact airframe design for such reasons as installation or accessibility requirements, the effect on vehicle LCC is included in the calculations.

Mathematical modelling of baseline costs during this phase is limited to the O&S phase, with inputs derived from detailed engineering, manufacturing, and financial analyses of the proposed design.

It is the individual design engineer and his immediate supervisor who are the key to controlling LCC. Included in the requirements for the components for which he is responsible will be unit cost, durability, reliability, and maintainability. The final design must be signed off by the responsible engineers in each of these disciplines to signify their concurrence that these requirements can be met. In the event that any of the assigned requirements cannot be met, the impact on the overall LCC is established and included in the review cycle shown in Figure 3.0. The process involved in establishing the LCC effect as set up for the GE-T700-401 is shown in Figure 4.0.

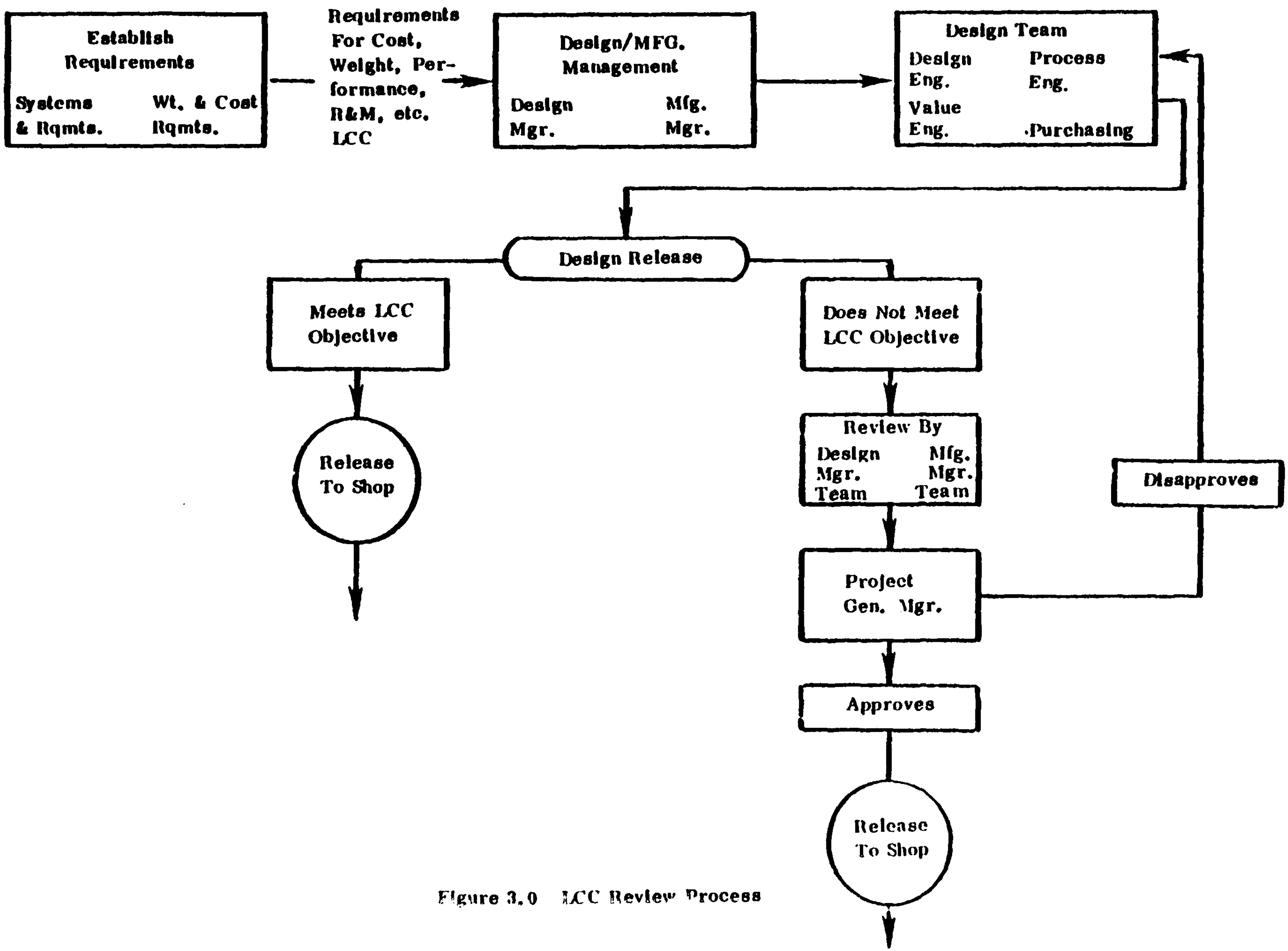
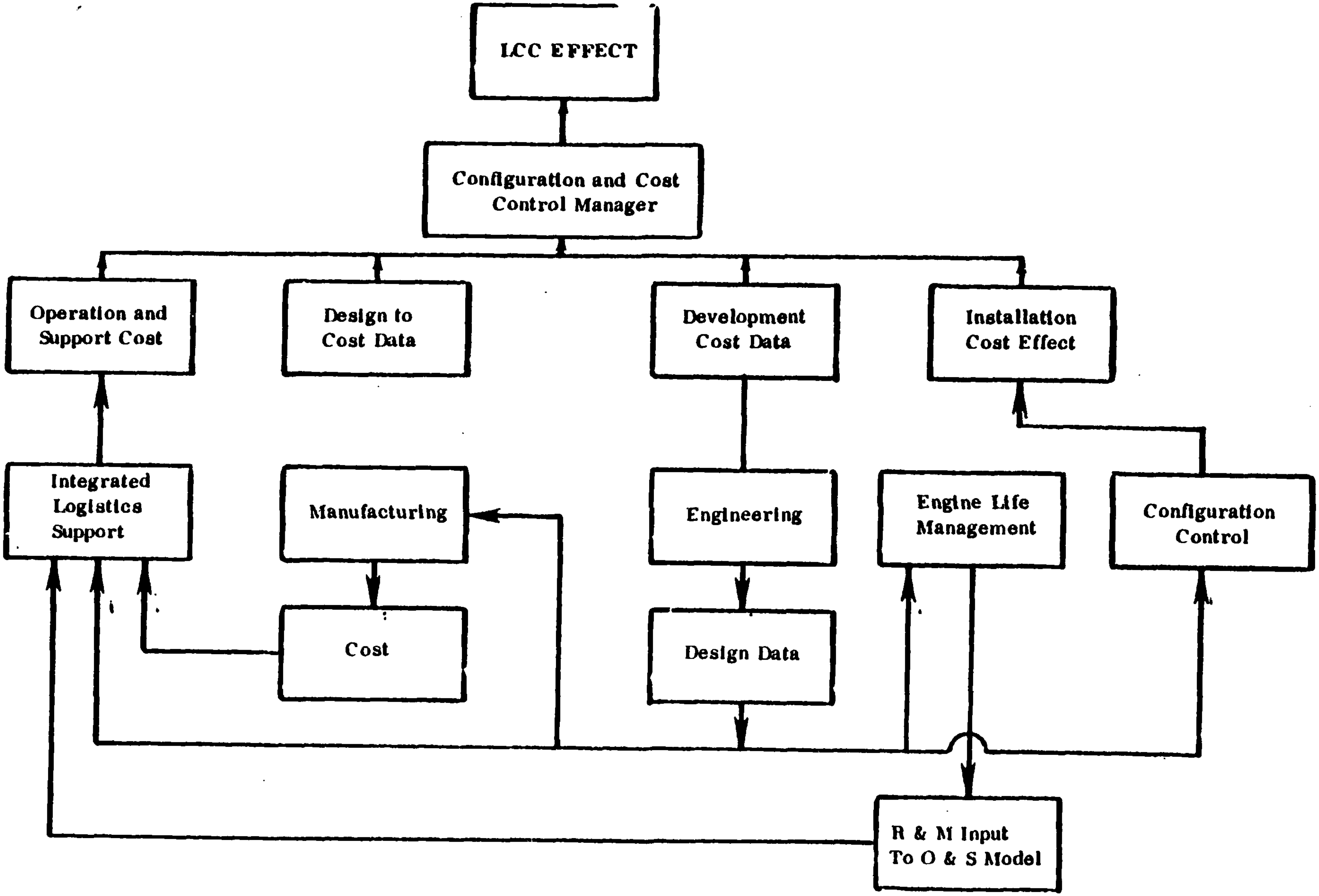
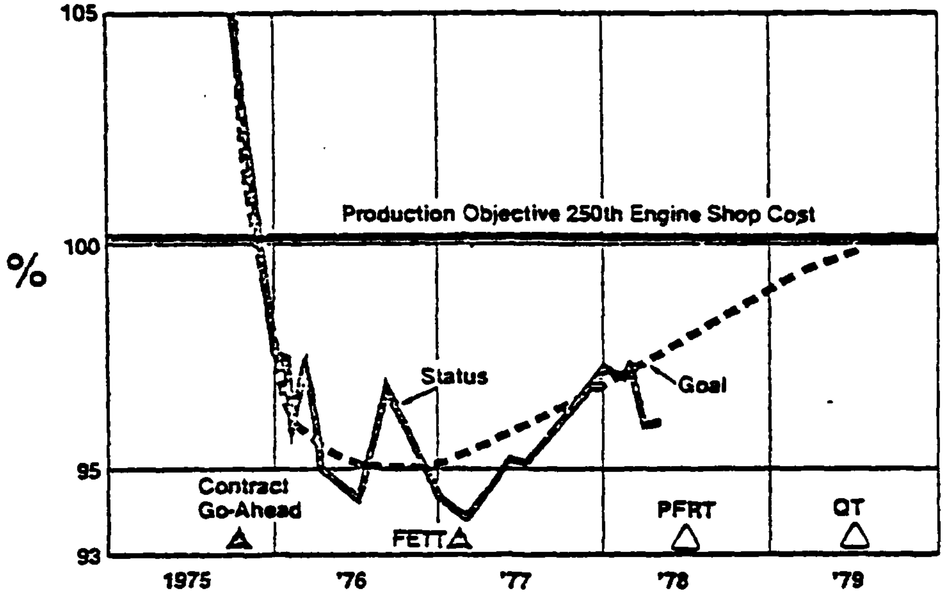


Figure 3.0 LCC Review Process



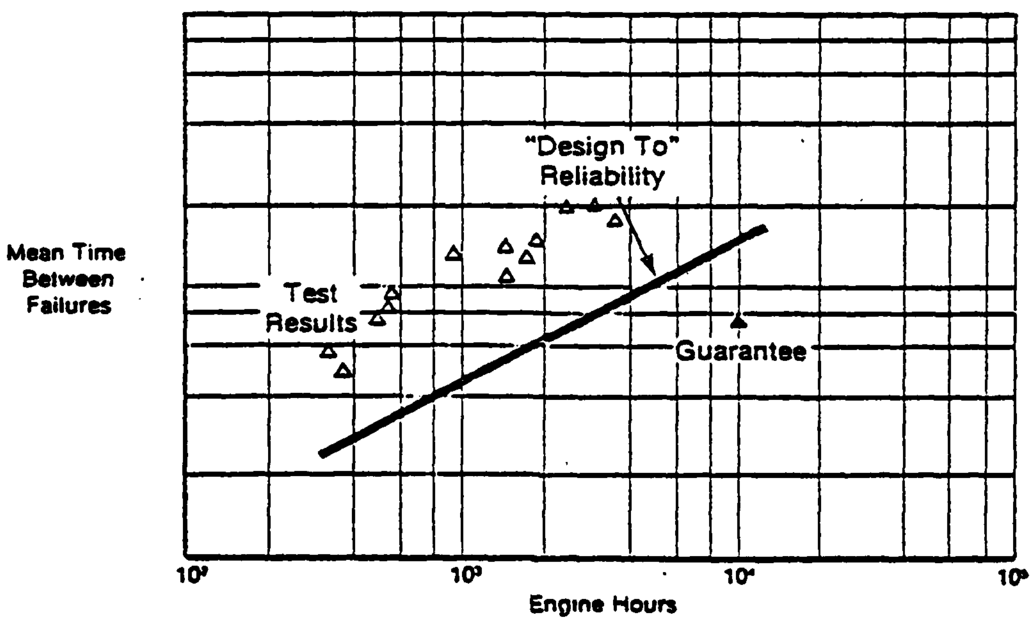
LIFE CYCLE COST REVIEW INFORMATION FLOW

FIGURE 4.0



DESIGN-TO-COST

FIGURE 5.0



F404-FSD RELIABILITY GROWTH GOAL

FIGURE 6.0

In addition to the above requirement to evaluate the component design for LCC impact, all LCC parameters which are subject to growth or evolution during the design and test phase are tracked. In the case of the F404, these are Unit Cost, Reliability, and Maintainability. In his paper on the F404, S. Bradley has shown our experience to date relative to Cost and Reliability, and Figures 5.0 and 6.0 are taken from his presentation. Maintenance Index as such cannot be measured directly during the development phase, but specific maintenance task times can. To this end, we have requirements on both the T700 and F404 engines to demonstrate these tasks at various stages during the development program. This serves the dual purpose of establishing the engine status relative to the final requirements and also validates the methodology used in estimating the task times upon which the overall engine maintenance index (and cost) is estimated. Furthermore, the continued emphasis, which results from the series of required demonstrations, results in continued improvement in the specified task time. Figures 7.0 and 8.0 illustrate this effect. These charts show the continued improvement from the first engine to test (FETT) through MQT as well as the specification requirement for the GE-T700-700.

The financial incentives to achieve the desired levels of LCC in the GE-F404-400 are associated with:

- Delivery cost of the first 520 engines
- Reliability at SMET, AST, and 10,000 engine flight hours
- Maintainability index at AST
- Parts usage cost at AST

Not directly incentivized, but specified as requirements to passing MQT, are various LRU and module removal and replacement times.

Thus, by controlling unit cost, reliability, and maintenance indices during the FSD phase, effective control of Acquisition Costs is accomplished.

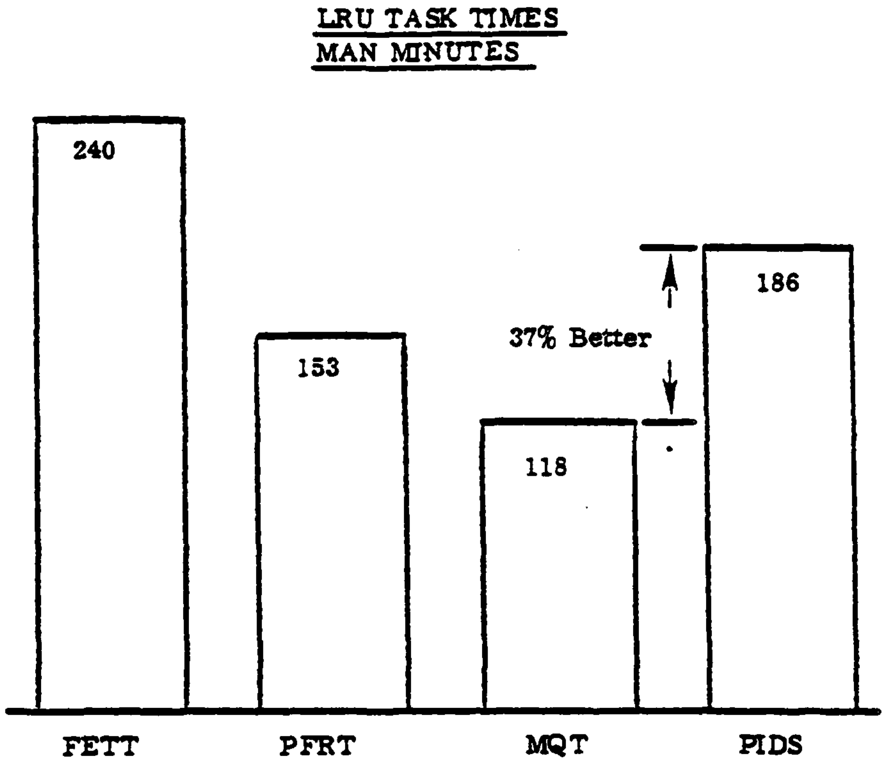


FIGURE 7.0

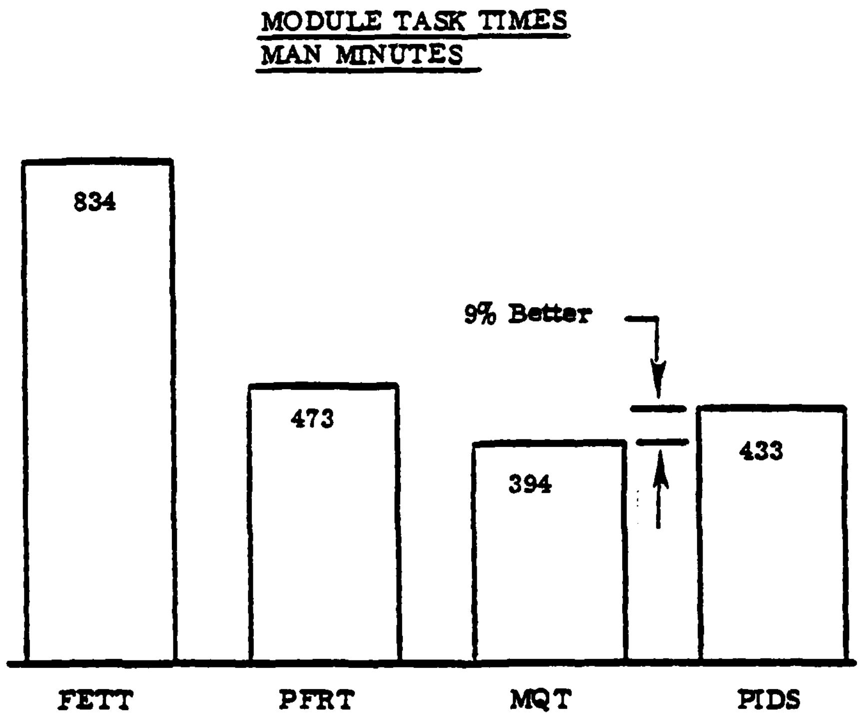


FIGURE 8.0

OPERATION & SUPPORT

LCC control during this phase rests not only on the engine contractor, but also on the customer. Currently, General Electric is required under contract to evaluate all proposed design changes to the T700, J85-21, and TF34 engines on an LCC basis. In the process of establishing a design change, the same decision process and tradeoff studies are accomplished as outlined under the FSD paragraph of this paper. Of particular significance in estimating the LCC impact of design changes is the consideration of the timing or phasing aspects. The time value of money cannot be ignored even if there is disagreement on the appropriate economic indices to be used. However, use of discounted cash flow techniques can significantly affect the break-even point as well as the overall cash benefit to be expected. It is interesting to note that the U. S. Army requires the contractor to use such techniques in the analysis of proposed T700 engineering changes.

The user can best control LCC by taking advantage of the low LCC features that have been designed into the engine. The T700 engine now entering U. S. Army service has been designed to achieve remarkably low maintenance indices and has successfully demonstrated these characteristics under field conditions. The demonstrated modularity, the elimination of special tooling at field level and the "no rig" philosophy that enables control system component changes to be made without control re-rigging or calibration will mean a reduction in the required maintenance manpower levels and skills relative to current inventory engines. Indicative of this are the relative task times recorded on the GE-T700-700 and a current Army helicopter engine, Table 2.0. These low maintenance attributes will also be a feature of the GE-T700-401 engine for the Navy LAMPS program. The Navy manning levels will, I am sure, reflect these improvements.

MAINTAINABILITY COMPARISON

	Current Army Engine	T700 Demonstrated
	Remove and Replace* (Man-Minutes)	
• AVUM Level		
- Fuel Control	115	8
- Fuel Manifold	157	14
- Anti-Ice/Bleed Vane	18	4
• AVIM Level		
- Power Turbine	144	64
- Stage 1 Turbine Wheel	361	72
- Combustor	310	96
• Depot Level		
- Special Tools	120	15
- Overhaul Interval	1800 Hrs.	On-Condition

*Demonstrated by Army Mechanics 1976

Table 2.0

SUMMARY

I have discussed the means by which we at GE attempt to realize the optimum LCC for our engines. We feel that we have been successful to date particularly on those engines where the customer has set requirements for LCC drivers and where we have jointly designed means of measuring these drivers during FSD or early in the operational phase. As pointed out in S. Bradley's paper on the F404, there is probably room for improvement in the method of providing incentives and permitting tradeoffs between the various cost drivers. I think it pertinent to repeat here my introductory remarks relative to LCC control requirements.

- Provide the individual design engineer with adequate tools in the form of LCC tradeoff relationships.
- Establish meaningful, measurable requirements for LCC drivers.
- Establish methods of tracking those LCC drivers subject to growth during the engine life cycle.
- Provide appropriate incentives to meet or better LCC driver requirements.
- Ensure that the user utilizes the full LCC potential in operating the engine.

IMPACT OF EARLY ENGINE USAGE DEFINITION ON LIFE CYCLE COST

Author: S. N. Finger

ABSTRACT

Life-limited parts represent a significant portion of a gas turbine engine, both physically and in acquisition cost. These parts are driven by usage; usage that may be significantly different for different applications and weapons systems characteristics. Life cycle cost modeling that recognizes the life-consuming usage events (rather than just engine operating hours) presents a more realistic cost picture.

INTRODUCTION

Life-Limited Parts

For purposes of this paper, gas turbine engine parts are classified as life- and nonlife-limited (or single event).

Life-limited parts tend to be those parts where the limiting mode results from long-term exposure to the entire range of normal operating events. Life-limited modes are creep, erosion, LCF, bearing fatigue, and affect a significant number of engine parts (Figure 1). These parts account for roughly 1/3 to 1/2 of the engine acquisition cost. Changes in usage (even within the normal operating range) will affect the life of these parts.

- **Disks**
- **Spacers**
- **Some cases**
- **Bearings**
- **Turbine blades**
- **Turbine vanes**
- **Combustor liners**

AV 135127

Figure 1. Life Limited Parts Represent a Significant Portion of the Engine

Nonlife-limited parts tend to be those parts where the limiting mode is an event in the normal operating range or an abnormal occurrence that drives the part out of its normal operating range. Single events such as overspeed/overtemperature (burst/yield), FOD, stall, contamination, and high frequency fatigue are examples of nonlife-limiting modes where the *single event* drives the part beyond limits. Nonlife-limited modes can also include quality, assembly, and overhaul error associated *single events*.

It should be noted that usage changes which "expand" the range of normal operation may take a life-limited part and create an event-limited part. (i.e., a gross rotor speed and temperature increase may cause an LCF-limited part to become yield limited.)

Events Which Drive Life-Limited Parts

The life of LCF-limited parts is determined primarily by the number and extent of thermally- and dynamically-damaging throttle transients. Throttle motions from shutdown to full power are typically most damaging, full throttle excursions from idle to full power are less damaging, and throttle motions of less than 20% rotor speed typically do little if any damage (Reference 1). In addition, rapid speed excursions tend to impose a more severe thermal gradient (and stress) than slow transients. Excursions that allow a part to see the full gradient may be more severe on some parts than rapid throttle excursions which turn around prior to the part experiencing the worst thermal stress.

Airfoil creep- and erosion-limiting modes are driven by time at high-power settings. References 1 and 2 point out a 10 to 1 creep life increase and a 3 to 1 erosion life increase with 100°F metal temperature reduction.

Thrust bearing fatigue life is classically determined based on thrust load, operating temperature, and rotor speed. The large impact of high speed, pressure, and temperature occurring simultaneously at high-power settings tends to make this the primary driver on thrust bearing also.

Obviously, the operating envelope has a significant impact on many life-limited modes, since high Mach number increases cooling air temperature and low altitude increases pressure levels. Similarly, any condition that tends to increase speeds, temperatures, and pressures (such as trim and inlet temperature variations) makes the operating environment more severe while conditions that decrease speeds, temperatures, and pressures (such as deterioration, installation, and inlet temperature variation) make the environment less severe.

GAS TURBINE ENGINE USAGE EXPERIENCE

With the above definition of life-consuming events, the next step is to relate the details of engine usage to these events. The following distinct usages will be addressed:

- Takeoff and Climbout
- Cruise/Ferry
- Primary Application
    - Air Combat
    - Air-to-Surface/TFR
    - High Mach
    - Training/Familiarization/Pattern Work
    - Ground Operation.
- Flight Length.

Takeoff and Climbout

The takeoff and climbout is frequently the most severe part of the mission from an LCF standpoint. This is because the engine has been at idle up to this time (except perhaps for a quick pop to full power on runup) and sees for the first time a full-power transient of extended duration resulting in a thermal as well as a centrifugal stress excursion. The extended time at high power on the takeoff and subsequent climbout is also significant from a creep/erosion standpoint.

Local restrictions and climb path play an important part in determining the amount of damage. The same aircraft flying at different bases may see full A/B takeoff at one, an intermediate power takeoff at another, and a combination w/power reduction at another; each being a function of local traffic, noise abatement, and carrier or shore-based operation.

Many aircraft perform a runup (check the engine at full power) prior to takeoff. Sometimes this is done in a runup area and sometimes at the end of the runway; either location can result in an LCF excursion from idle to full power.

Cruise, Ferry

Cruise and ferry are characterized by long periods at constant power setting, doing few if any significant throttle excursions. For low thrust-to-weight aircraft, this power setting could be high enough to cause some erosion damage.

Air refueling is similar to cruise segment except that an idle to full-throttle transient may occur on breakaway from the tanker.

Primary Application

Experience has shown that, in terms of life-consuming events, (time at full power-creep and erosion, idle to full power throttle transients-LCF) aircraft thrust-to-weight has a significant impact. Early weapons systems tended to be low thrust/weight and needed a large amount of time at full power to accomplish the mission. High thrust-to-weight aircraft, on the other hand, tend to "throttle back" further and more frequently resulting in less time at full power and more full throttle excursions.

The following information is derived from pilot interview, aircraft records, and engine event recorder. It is based on peacetime tactical *training* syllabus data. It is felt that since wartime use has historically accounted for a small percentage of total engine time that the largest impact to life will be this tactical simulation of combat environment.

Air Combat

Air combat engagements last for several minutes followed by cruise periods and set up for re-engagement. Data from several engines in an Air Combat Maneuvers (ACM) situation show that for low thrust/weight aircraft the entire engagement is spent at full power while for high thrust/weight aircraft as many as 3 to 4 full-throttle transients per engagement may be experienced. Frequent use of afterburner is also characteristic. Air engagements generally take place between 0.4 to 0.9 Mn and 10 to 30K altitude. Recognizing that many factors (number of combatants, threat, armament, etc.) account for scatter in the usage during air combat, figures 2 and 3 show the ACM damaging events as a function of weapons system maximum takeoff thrust to maximum takeoff weight.

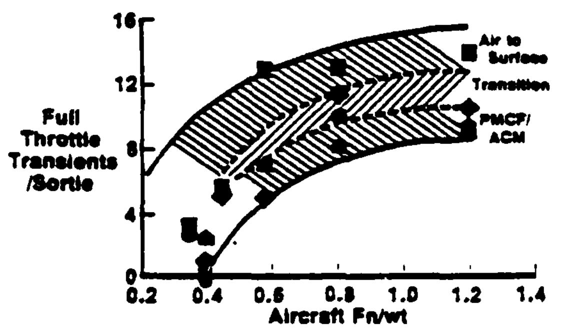


Figure 2. Hi Thrust to Wt Aircraft Do More Full Throttle Transients

Air-to-Surface/Terrain Following (TFR)

Air-to-Surface activity (bombing) is driven by number of passes per mission and by delivery type. Level-type deliveries require little throttle motion, diving, and high-angle deliveries generally result in a full-throttle transient on each delivery. Since both TFR and air-to-surface occur at low altitudes, the higher inlet temperature and pressure is felt in higher engine speeds, temperatures, and pressures.

Terrain following experience has shown that, over a variety of terrains, while many small-throttle transients occur (less than 3% speed), typically 2 to 6 full-throttle excursions are required per TFR segment. Furthermore, these transients to full power are of short duration resulting in only a small contribution to creep/erosion damage.

On our thrust-to-weight curve, while the trend will remain the same, it is apparent the air-to-surface activity results in more *throttle motion than air combat and less time at full power.*

High Mach Number

Going to high Mach numbers and high altitudes tends to result in fewer throttle transients and more time at full power. The long hold time at full power associated with climbout and the high engine inlet temperature reached make this the most severe operating condition from a creep/erosion standpoint. The creep damage above Mach 2.0 is many times as severe as in the subsonic environment.

One example of high Mach number usage is the post maintenance check flight activity where the engine is taken to some altitude/Mach number threshold for acceptance following significant maintenance. This functional checkout occurs infrequently (less than 5% of total usage). Figure 3 shows that in terms of full-power time this activity is as severe as ACM, but since much of this full-power time is at high Mach number it is actually more severe.

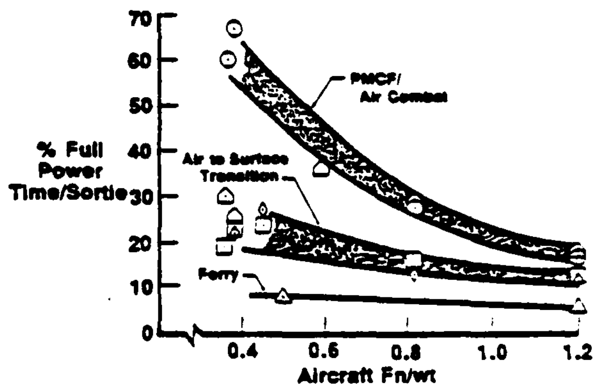


Figure 3. Full Power Time Usage Decreases With Increasing Thrust to Wt

Transition/Familiarization/Pattern Work

Transition activity is training a pilot to a new weapons system. Pattern work and touch and go's generally require a full-throttle transient and are a major part of the transition flights. Familiarization involves specific maneuvers (taking aircraft to stall, turning, banking, and rolling) many of which require full-throttle excursion. Add to this the aspect of the pilot becoming familiar with the engine/aircraft which tends to result in excessive throttle use. The result is that transition sorties are second only to air-to-ground activities in full-throttle transients.

Flight Length

The number of shutdown to full-power throttle transients an engine will see in its "engine flight hour" lifetime is largely determined by the length of its flights. Specific missions, tailored to a particular system, dictate the flight length. Although there is a wide variation, experience shows some trends.

Figure 4 shows that ferry, patrol flights are ~3 to 4 hours long, TFR/bombing flights are 2 to 3 hours long, air-to-surface flights are 1.5 to 2.0 hours long, air combat is 1 to 1.5 hours long, and post maintenance check flight is about 1 hour long.

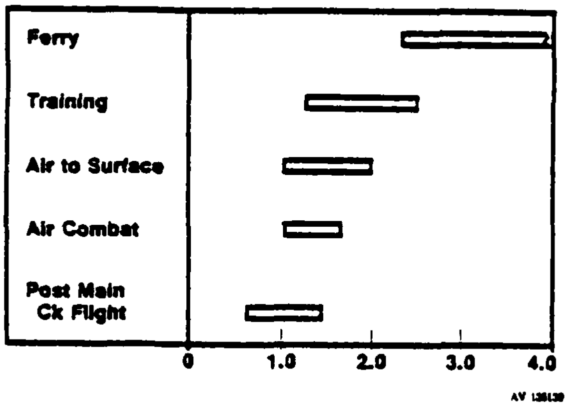


Figure 4. Typical Flight Lengths

Ground Operation

Ground operation includes installed trim, troubleshooting, taxi and idle to maintain aircraft electronic and environmental systems. It also includes test stand trim, troubleshooting and acceptance test.

The *test stand* operation, being uninstalled, tends to see slightly higher operating speed, temperature and pressures. Depending on application (i.e., takeoff path and maximum Mn in sortie), this may be a *worse* condition than many seen in flight.

At any event the trim and test stand usage typically has long hold times at high power, several idle to full power throttle transients (which combined with long hold times ensure the parts to see the maximum thermal gradient) and frequent A/B lights. For these reasons test stand/trim operation is significant in life-limited part considerations.

Engine experience shows that ground activity (trim, test stand) occurs about every 100 engine flight hours on mature engines. Average test stand/trim operation tends to be pretty standard involving several full-throttle transients and about half an hour at full power per trim or test stand occurrence, although there are significant variations due to troubleshooting/trim problems.

It is interesting to note that for higher thrust-to-weight weapons systems this ground activity tends to contribute a larger portion of the total full-power time damage. This is shown in figure 5 and is due to the decrease in overall high-power time associated with high thrust/weight aircraft.

USAGE VARIATION

The preceding curves reflect usage variation from a variety of sources. Some recent military engines have damaging event tracking devices. These recorders count life-consuming events (time at full power and cycles) per flight. Results of this data show that a significant variation in a given sortie type is seen due to pilot-to-pilot variations, engine-to-engine variations, weather conditions, etc. (figure 6).

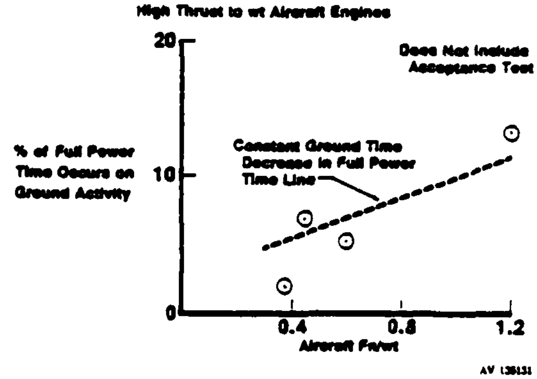


Figure 5. Ground Activity Represents a Larger % of High Power Time

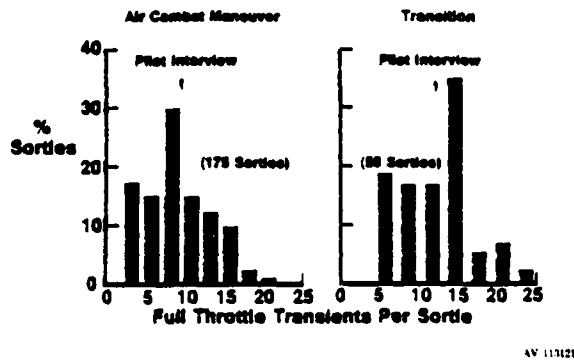


Figure 6. Variation in Life Consuming Events Per Sortie

It is interesting, however, that at a given base much of this "washes out" when the individual sortie type is mixed with the entire syllabus, over a long period of time (figure 7).

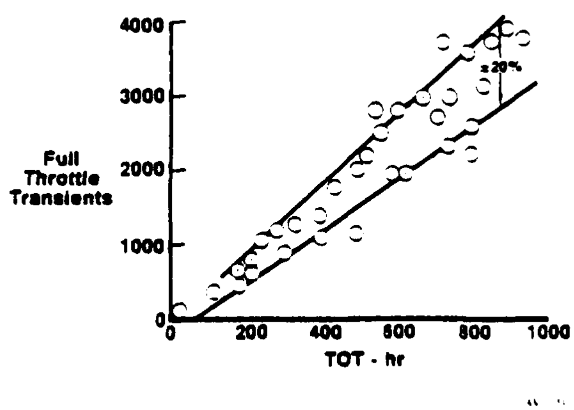


Figure 7. 20% Engine Usage Variation at a Base

There remains about a ±20% variation in usage at a particular base. Base-to-base variation is larger.

IMPACT ON LCC STUDIES AND MODELS

With the preceding background in usage, it is not surprising that an engine sees an extremely different usage depending on which base, command, or aircraft system it is in. Further, it becomes obvious that to base LCC predictions and assessments solely on engine flight hours becomes very questionable. Actual field engine data and mission test data show that scrappage rate correlates with damaging events — not necessarily engine operating time (figure 8).

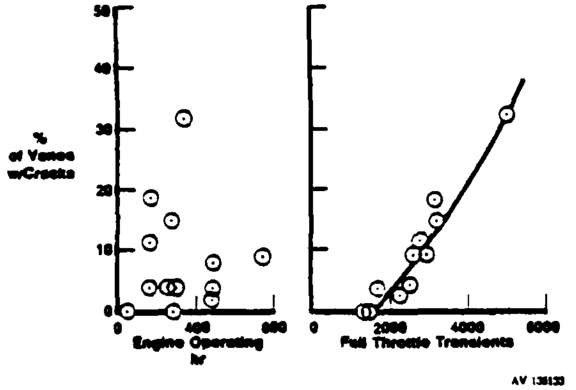


Figure 8. Distress Correlates With Damaging Event

Since much of the damage for life-limited parts is accrued from time at full power and full-throttle transients, it makes more sense to correlate these parameters with engine flight hours and construct LCC models that address these drivers. LCC models have been created in the conceptual phase of design using the previous information for a gross definition of expected usage and its tie to engine flight hours (EFH) i.e.:

EFH/Year — *Replacements/EFH*

Full-Throttle Transients/EFH

Hot Time/EFH

*$/replace

Life Requirement in Time or EFH

Using this concept an engine in a low thrust-to-weight aircraft flying air combat mission would see about 1/4 the cycles but about 4 times the hot time per flight hour of a high thrust/weight aircraft flying an air to surface mission (figure 9). The resulting LCC analysis reflects this in early replacement of hot section (creep and erosion limited) parts on the former mission but longer disk and rotating (LCF limited) part lives.

While this sort of simplified approach is a step toward recognizing the impact of usage in conceptual definition and early phases of LCC evaluation, once actual design has begun and part lives have been calculated the sensitivity of these parts to usage changes can be assessed. This sensitivity analysis recognizes that different parts are impacted to different degrees by usage changes.

A parametric approach has been employed with good results in defining the parts life sensitivity, not only to the number of life-consuming usage events but also to the particular engine designs response to the usage.

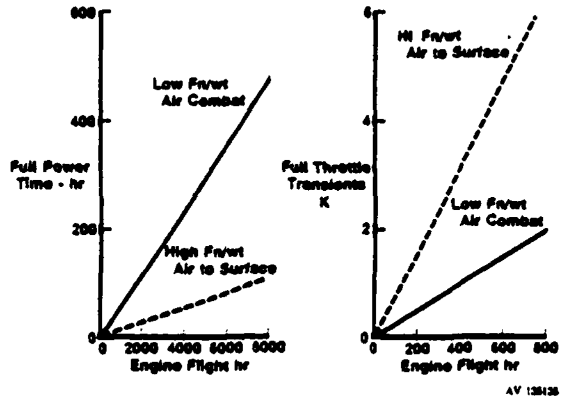


Figure 9. Life Consuming Usage

Figure 10 shows the logic employed in these LCC studies. LCC models of this sort are useful in assessing optimum design concept, downtrim, alternate applications, effects of usage or control system changes, or combinations of these items. Feeding the usage definition *and* parametric life sensitivity information for representative parts into the LCC model provides a more realistic assessment of the engine cost picture.

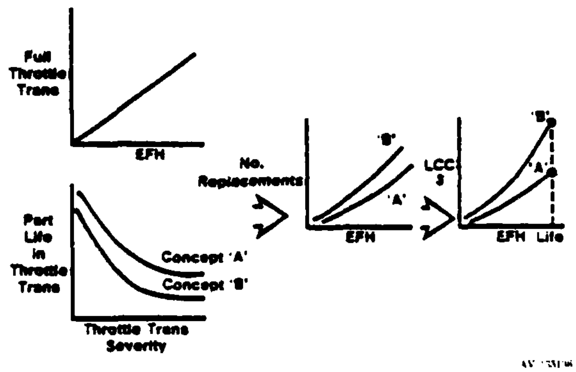


Figure 10. LCC Model Considering Life Consuming Usage

IMPACT ON LCC IN THE FIELD

Usage definition also enters the LCC picture in the reduction of overall LCC in terms of required maintenance.

Maintenance based on recorded "life drivers" rather than engine flight hours can keep parts operating longer, optimize the part replacement interval, and minimize chances of premature failure. The life-consuming event counter can be used to set inspection intervals and replacement times for life-limited parts. Figure 11 shows that if engine time were used to set the inspection interval, (for life-limited distress) some parts would be replaced prematurely or else some parts would fail prior to the inspection period.

Another impact on LCC is that once usage is identified "duplicate driver" testing can be constructed. These simulated mission tests may take the form of real time engine tests, accelerated engine tests, or specialized lab and rig tests. In any of these forms these tests can duplicate the desired aspects of field usage and uncover problems, prior to fleet impact thus allowing time for corrective action.

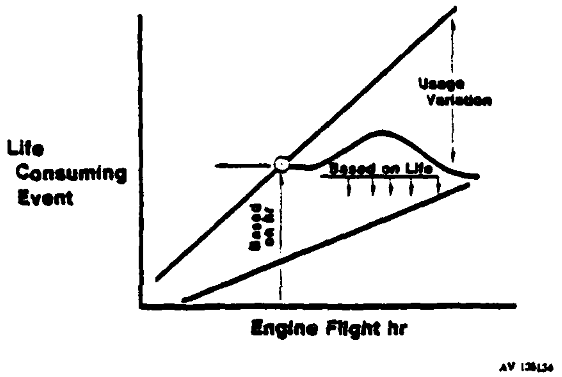


Figure 11. Inspection Based on Usage/Allows Longer Service

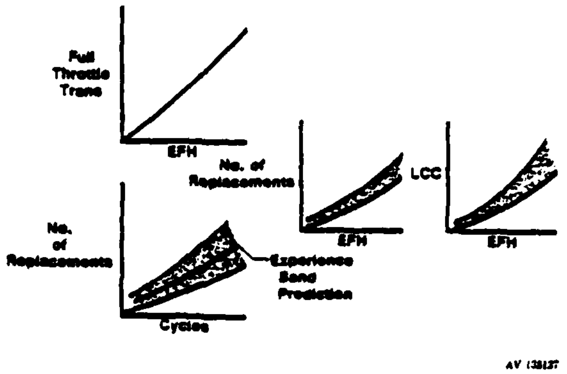


Figure 12. LCC Model Updated With Actual Experience

Actual experience has used the LCC model built during the design phases and modified it to include mission test, lead-the-fleet-scrappage, and teardown results to serve as a base for projecting provisioning and to evaluate LCC impact of hardware changes. (Figure 12 shows this concept.)

SUMMARY

In summary, life-cycle cost modeling of engine life-limited parts is being pursued based on life-consuming usage rather than just engine flight hours. Significant effort is being expended to quantify and track this usage for use early in the conceptual LCC models as part of design LCC models and through development and field operation LCC studies.

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2. Sellers, R. R. and W. F. Zavatkay, "Life Considerations in the Engine Design Process," AIAA paper, 7/11/77.

CALCULATING TURBINE ENGINE LIFE CYCLE COST

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ABSTRACT

A Turbine Engine Life Cycle Cost (LCC) methodology was developed for use during Air Force source selection. The methodology itself is a consistent process that defines and organizes all engine chargeable costs. It can discriminate between engine designs and can be tailored to accommodate the amount of detailed information known about the engine at the time of the source selection. At the present time, the equations, definitions, and specific ground rules are complete. Several tasks are required, eventually bringing the model to a full-scale demonstration prior to its use. Potentially, this model can provide logical and consistent engine LCC information to future source selections.

INTRODUCTION

Previous Air Force turbine engine source selections indicate improvements in estimating LCC of proposed engines are desirable. In the past, each Air Force turbine engine source selection has applied different ground rules to estimating turbine engine LCC. Each source selection used its own definition and used different sources of Air Force data for the turbine engine LCC estimates. Moreover, LCC models previously used were not originally intended for use in source selection. These models were not tailored to the pertinent engine cost data available at the time of engine source selection.

This paper describes the LCC methodology developed by the Joint Air Force/Industry Working Group. This methodology is to be used in all future Air Force engine source selection, including those times when the engine is Contractor Furnished Equipment (CFE). This paper covers the development of the working group, the working group's approach to developing engine LCC methodology, and the resulting methodology. The paper also outlines future work necessary before the methodology can be used in source selection, and the anticipated benefits of model use.

The author acknowledges J. R. Kline and D. S. Williams for their 1976 work on this subject, as is outlined in the published paper, "Joint AF/ Industry Engine LCC Methodology".

PROCEEDINGS OF THE AIR FORCE/INDUSTRY WORKING GROUP

Invitations were sent to engine and airframe contractors and applicable government agencies to attend a July 1975 conference on the problem of estimating engine LCC during source selection. The problem was presented

and attendees discussed their past efforts in estimating engine LCC. As a result of this meeting, a working group was formed to develop engine LCC methodology.

The working group was composed of representatives from all USA engine contractors, several USA airframe contractors and Air Force personnel from Aeronautical Systems Division (ASD) Engineering, Air Force Aero Propulsion Laboratory, and Air Force Logistics Command. The initial meetings of the working group were attended by Army personnel. This group continued to meet every six weeks over a period nine months.

The working group's objective was to develop engine LCC methodology. The required methodology includes engine LCC model equations; terms, symbols, and definitions; and general instructions for engine LCC model use. The engine LCC model must account for all Research, Development, Test, and Evaluation (RDT&E), Acquisition and Operations and Support (O&S) costs. The model must discriminate between the candidate engine designs. In addition, the model must be tailored to the data available in a particular engine source selection.

The working group divided itself into three committees, each committee addressing a separate phase of LCC (RDT&E, Acquisition, and O&S). During each meeting, RDT&E, Acquisition, and O&S committees would meet independently, after which the entire working group would assemble to discuss the progress of the separate committees. When duplication of model equations became obvious, an integration committee was created to fuse together the work separately developed by the three committees. The integration committee also provided the general instruction for model use.

Model equations; terms, symbols, and definitions; and general instruction for model use, were completed at the conclusion of the working group's tenure. A draft report of the engine LCC methodology was published and distributed to industry for comments. The methodology was then briefed to ASD. However, several tasks remain to be completed before the engine LCC methodology is ready to be used in a source selection.

ENGINE LCC MODEL EQUATIONS

The engine LCC model has 24 equations. Most of these equations are used in more than one phase of LCC: 22 equations are used to calculate RDT&E costs, 14 equations to calculate Acquisition costs, and 16 equations to calculate O&S costs. A short summary of each equation is given below.

Conceptual Study and Configuration Cost

Determines direct conceptual study cycle and engine configuration costs based on engineering man-hours and a composite engineering hourly rate.

Mock-Up Costs

Mock-up cost is based on labor cost, materials, and other direct costs.

Detailed Engine Design Cost

Detailed engine design cost is based on the design and drafting man-hours, the design and drafting composite hourly rates, and the other direct costs for each engine section.

Tooling Costs

The tooling cost equation collects the tooling material and labor for each engine section. The equation also collects all non-engine tooling costs.

Engine Manufacturing Costs

Engine manufacturing costs are determined by breaking down the engine into its sections, assemblies, and part levels. The engine level required depends on the particular source selection. Material, labor, and other direct costs are collected at the required level.

Cost of Spare Engines, Assemblies and Parts

This equation calculates engine spare parts cost based on the back order standard, the repair cycle time, and ordering and shipping times.

Peculiar Support Equipment Cost

Peculiar support equipment cost is computed based on labor and material required for equipment design and manufacture.

Common Support Equipment Cost

Common support equipment cost is calculated for all organizational levels based on AFLC supplied inputs.

Special Test Equipment Cost

Special test equipment cost is calculated for all organizational levels.

Packaging and Shipping Cost

This equation accounts for the packaging and shipping costs of all engine, spare parts, Aerospace Ground Equipment (AGE), training equipment, and test equipment.

Facilities Cost

This equation captures the cost for new and modified facilities. Facilities cost is based on the cost to design, build, and check out both contractor and government facilities.

Contractor Test Costs

Contractor test costs are based on the Petroleum, Oils and Lubricants (POL) costs, the test hours, and the direct costs per test hour for each engine section.

Government Test Costs

Government test costs are based on the cost of tests conducted at various test sites.

Training Cost

Training costs are computed for initial contractor and both initial and recurring government training. Costs are based on the number of different courses at various organizational activities.

Contractor Field Support Costs

Field support costs are accumulated for both home office and field service efforts.

Data Costs

Data costs include costs for technical orders and technical manuals, plus the initial and recurring cost of data management.

Initial Inventory Management Cost

This equation contains the cost to introduce new items into the supply system.

Recurring Inventory Management Cost

This equation computes the management cost of both items in the wholesale inventory system and in the base supply system.

Engine Scheduled Maintenance Cost

The engine scheduled maintenance cost equation computes the cost of scheduled inspections and the scheduled time change costs for base, depot, and contractor maintenance.

Engine Unscheduled Maintenance Cost

This equation calculates the unscheduled on-equipment maintenance and unscheduled off-equipment maintenance cost for base, depot, and contractor maintenance.

Recurring Maintenance Management Data Cost

This equation computes the maintenance management data costs for both scheduled and unscheduled maintenance.

Systems Engineering/Project Management Costs

This equation accounts for costs defined in Paragraph 40.2.5 of MIL-STD-881A that cannot be related to a specific hardware or task item.

POL Cost

This equation accounts for the cost of the fuel consumed during ground run time, the fuel consumed during overhaul acceptance runs, and both the fuel and oil consumed during missions.

Production Program Start-Up Costs

Production program start-up costs are based on the labor and material required for initial production setup, configuration audit, etc.

TERMS, SYMBOLS, AND DEFINITIONS

Each of the equations previously described has several input terms. These terms were symbolized in computer format, and each term was completely defined. Definitions were formulated for other terms to provide clarity in using the methodology. The source of each input term was identified as engine contractor (EC), AFLC standard (LS), model generated value (M), program office (P), systems integration contractor (SC) or using command (U).

GENERAL INSTRUCTIONS FOR ENGINE LCC MODEL USE

The general instructions present the guidelines for model use during engine source selection. These instructions outline the intended use of the engine LCC source selection model. The model was developed to be used only in source selections as opposed to other areas such as implementing warranties. The model does not give absolute engine LCC but can compare the LCC of alternate engine designs. The model was designed to break down the engine to the part level. However, this capability should be used only as required. Of the 24 equations in the engine LCC model, only the important ones should be used. Costs are shown in fiscal years and will include General and Administrative cost (G&A), but will exclude profit and fee.

The instructions also outline the Air Force's and the contractor's responsibilities during source selection. The Air Force is responsible for providing the computer program listing, the computer cards/tapes, the verification test cases, and the users manual for the engine LCC model. The Air Force will provide the AFLC standard, the program office, and the using command inputs. The contractor is responsible for providing a

listing of all contractor inputs, and providing a computer listing of the LCC model results.

SAMPLE MODEL EQUATION

The POL equation is used as an example to illustrate the data required for this model. The POL cost is output in dollars/fiscal year.

$$CPOL = \overset{1}{(CFG)\ (GPHG)\ (AEFH)\ (EGR)}$$

$$+ \overset{2}{\sum_{n=1}^{NKFM} \left[(AEFHM_n)\ (CFG)\ (GFHF_n) \right]}$$

$$+ \overset{3}{\sum_{n=1}^{NKFM} \left[(COG)\ (GPHO_n) \right]}$$

The first part of this equation calculates the cost of fuel consumed in ground run time. The second part calculates the cost of fuel and oil consumed during missions. The third part computes the cost of fuel required in overhaul acceptance runs.

The definitions and input sources of the terms in the POL equation are shown below:

AEFH	Annual engine force flying hours (U)
$AEFHM_n$	Annual engine force flight hours for nth specified flight mission (U)
CFG	Fuel cost per gallon (LS if government furnished, EC if contractor furnished)
COG	Oil cost per gallon (LS if government furnished, EC if contractor furnished)
CPOL	Cost of POL (M)
EGR	Number of hours of ground running per engine flight hour (U)
$GPHF_n$	Gallons of fuel per hour of operation for the nth specified flight mission (EC and SC)

GPHG	Gallons of fuel per engine ground run hour (EC and SC)
$GPHO_n$	Gallons of oil per hour of operation for the nth specified flight mission (EC)
GPOHA	Gallons of fuel per overhaul acceptance run (EC)
n	Integer subscript value
NKFM	Number (kind) of flight missions (U)
NNOHA	Number of overhaul acceptance runs per year (EC)

TAILORING THE ENGINE LCC MODEL

The model should be tailored to a particular source selection. The objective is a model that is design sensitive and can distinguish between alternate engine designs. For a particular source selection, only those equations that are design sensitive and capture over 90% of RDT&E, Acquisition, and O&S costs should be used. For a 2000 fighter aircraft engine buy, the equations shown below contribute over 90% of RDT&E, Acquisition, and O&S costs.

% RDT&E

Detailed Engine Design Cost	15%
Engine Manufacturing Cost Cost of Spare Sections, Assemblies and Parts	35%
Contractor Test Cost	30%
System Engineering/Project Management Cost	7%

% Acquisition

Tooling	3%
Engine Manufacturing Cost	85%
Packaging and Shipping	<8%

% Operations & Support

Engine Scheduled Maintenance	
Engine Unscheduled Maintenance	
Packaging & Shipping	6%
POL Cost	30%

FUTURE MODEL DEVELOPMENT

The Air Force/Industry Working Group issued a draft report of their methodology titled "Turbine Engine Life Cycle Cost Model", dated 1 Feb 77. Several tasks were identified for follow-on effort before the methodology could be used in source selection. These tasks are: (1) reviewing the model equations for accuracy; (2) incorporating on condition maintenance/ turbine engine monitor system LCC prediction capability; (3) computer programming the engine LCC model; (4) running verification test cases in the computer program; (5) writing a users manual for the computer program; and (6) refining the instructions for the engine LCC model use.

The time frame for the completion of these 6 tasks has not been identified.

CONCLUSION

The Turbine Engine Life Cycle Cost Model provides logical and consistent methodology to estimate engine LCC in future engine source selections. The methodology contains a systematic way to tailor the model to a particular source selection

EVALUATING ENGINE LIFE CYCLE COST AT SOURCE SELECTION

- SOURCE SELECTION LCC GROUND RULES
  - UNIFORM DEFINITIONS
  - UNIFORM SOURCES OF DATA INPUT
  - CONSISTENT USE OF MODELS
- LCC MODELS ARE TO BE TAILORED TO THE SOURCE SELECTION
- LCC MODELS ARE TO BE DESIGN SENSITIVE

Chart 1

OBJECTIVE

DEVELOP A LCC METHODOLOGY TO AID INDUSTRY AND THE AIR FORCE IN FUTURE ENGINE SOURCE SELECTIONS

- LAYOUT GROUNDRULES FOR LCC ANALYSIS
- ESTABLISH LCC TERMS AND DEFINITIONS
- BUILD A LCC MODEL THAT:
  - ACCOUNTS FOR ALL RDT&E, ACQ, AND O&S COSTS
  - DISCRIMINATES BETWEEN ALTERNATE ENGINE DESIGNS
  - CAN BE TAILORED TO A PARTICULAR SOURCE SELECTION

AIR FORCE/ARMY/INDUSTRY INVOLVEMENT

AIR FORCE

- AERONAUTICAL SYSTEMS DIVISION
- AIR FORCE LOGISTICS COMMAND
- AERO PROPULSION LABORATORY

ARMY

- ARMY AVIATION SYSTEMS COMMAND

INDUSTRY (ENGINE)	INDUSTRY (AIRFRAME)
AVCO LYCOMING	BOEING
WILLIAMS RESEARCH	McDONNELL
GENERAL ELECTRIC	VOUGHT
DETROIT DIESEL ALLISON	GRUMMAN
PRATT & WHITNEY	GENERAL DYNAMICS
AIRESEARCH	LOCKHEED
TELEDYNE CAE	

Chart 3

AIRCRAFT ENGINE LIFE CYCLE COST WORKING GROUP

- ENGINE LCC WAS DIVIDED INTO THREE PHASES

  RDT&E, ACQUISITION, AND O&S

  A COMMITTEE WAS FORMED TO HANDLE EACH PHASE AS A ENGINE LCC SUBMODEL

  - COST AREAS WERE DEVELOPED INTO EQUATIONS
  - DEFINITIONS WERE ESTABLISHED

- AN INTEGRATION TEAM PROVIDED STANDARDIZATION OF EQUATIONS & DEFINITIONS

  - ALLOWED EQUATIONS TO BE USED IN MORE THAN ONE LCC PHASE
  - PROVIDED INPUT SOURCE
  - OPERATING INSTRUCTIONS FOR MODEL USE

Chart 4

MODEL EQUATIONS

TITLE	RDT&E	A	O&S
Conceptual Study, Cycle and Configuration Cost	X		
Mockup Cost	X		
Detailed Engine Design Cost	X		X
Tooling Cost	X	X	
Engine Manufacturing Cost	X	X	X
Cost of Engine Spare Sections, Assemblies & Parts	X	X	
Peculiar Aerospace Ground Equipment Cost		X	X
Common AGE Cost	X	X	
Special Test Equipment Cost	X	X	X
Packaging and Shipping Cost	X	X	X
Facilities Cost	X	X	
Contractor Test Cost	X		X
Government Testing Cost	X		X
Training Cost	X	X	X
Contractor Field Support Cost	X	X	X
Data Cost	X	X	X
Initial Inventory Management Cost	X	X	
Recurring Inventory Management Cost	X		X
Engine Scheduled Maintenance Cost	X		X
Engine Unscheduled Maintenance Cost	X		X
Recurring Maintenance Management Data Cost	X		X
System Engineering/Project Management Cost	X	X	X
POL Cost	X		X
Production Program Startup Cost		X	

Chart 5

POL COST

$$\text{POL} = \underset{1}{\text{FUEL CONSUMED IN GROUND RUN TIME}} + \underset{2}{\text{FUEL AND OIL CONSUMED DURING MISSIONS}} + \underset{3}{\text{FUEL REQUIRED IN OVERHAL ACCEPTANCE RUNS}}$$

$$1 = (CFG)\ (GPHG)\ (AEFH)\ (EGR)$$

$$2 = \sum_{n=1}^{NKFM} \left[(AEFHMn)\ (CFG)\ (GPHFn) + (COG)\ (GPHOn) \right]$$

$$3 = (CFG)\ (GPOHA)\ (NNOHA)$$

Chart 6

ESTIMATED COST CONTRIBUTION FOR A NEW FIGHTER ENGINE

% RDT&E	
DETAILED ENGINE DESIGN COST	15%
TOOLING COST	5%
ENGINE MANUFACTURING COST; COST OF SPARE SECTIONS, ASSEMBLIES AND PARTS	35%
CONTRACTOR TEST COST	30%
SYSTEM ENGINEERING/PROJECT MANAGEMENT COST	7%

% ACQUISITION	
TOOLING	3%
ENGINE MANUFACTURING COST	85%
PACKAGING & SHIPPING	< 8%

% OPERATION & SUPPORT	
ENGINE SCHEDULED MAINTENANCE; ENGINE UNSCHEDULED MAINTENANCE	62%
PACKAGING & SHIPPING	6%
POL COST	30%

Chart 7

PROPOSED ACTIONS FOR FOLLOW-ON LCC MODEL DEVELOPMENT

- REVIEW MODEL EQUATIONS FOR ACCURACY
- INCORPORATE ON CONDITION MAINTENANCE/TURBINE ENGINE MONITOR SYSTEM LCC PREDICTION CAPABILITY
- COMPUTER PROGRAM ENGINE LCC MODEL
- RUN VERIFICATION TEST CASE IN COMPUTER MODEL
- WRITE INSTRUCTIONS FOR LCC COMPUTER MODEL USE AND USERS MANUAL

Chart 8

BENEFITS

- o ASSURES CONSISTENT AND EFFECTIVE COMMUNICATION BETWEEN CONTRACTORS AND THE AIR FORCE
- o LETS THE AIR FORCE COLLECT ONLY THE LCC DATA THEY NEED
- o ALLOWS THE GOVERNMENT TO MAKE BETTER USE OF LCC DATA DURING SOURCE SELECTION

Chart 9

PRODUCTIVITY IN ENGINE MANUFACTURING

Frank J. Fennessy, Manager
Manufacturing R&D
Pratt & Whitney Aircraft Group
Manufacturing Division
East Hartford, Conn. 06108

PRODUCTIVITY IN ENGINE MANUFACTURING

My topic today is "PRODUCTIVITY" - a widely used and abused term.

WHAT IS PRODUCTIVITY?

I have seen hundreds of definitions of "Productivity" and the best one I have derived is as follows:

SLIDE 2

"Productivity is a measure of management's effectiveness in employing all the necessary resources...human, natural and financial." Notice that I say MEASURE - and I mean measure.

By HUMAN I mean people, motivation, job enrichments, etc.
By NATURAL I mean use of natural resources, tools, methods, power.
By FINANCIAL I mean capital to buy these things.

SLIDE 3

This slide asks: "Why should we do it?"

I am certain that this is self-explanatory.
By the way, the ID/OD gauge shown here and used by us by the thousands, was developed 20 years ago and has saved us in excess of $20 million dollars.

When we started work on this in 1957, we paid $900 for an ID/OD gauge for a specific dimension. We wanted a gauge that could be adjusted 6" in diameter and 2" in depth. At last report, we had over 15,000 of them in all plants and now it is a national standard.

SLIDE 4 - Shows that technology represents 38.1%.

In a study last year by Data Resources, Inc., it was found that high technology industries "grew nearly 3 times as fast, at double the productivity record and had significantly lower inflation impact than low technology industries."

SLIDE 5 - Shows factors which result in an increase in productivity.

SLIDE 6 - This slide is self-explanatory. We are working to improve our internal operations.

When I started this job 9 years ago, I found direct labor to be less than 10% of product cost. Overhead was level, with material cost skyrocketing. We were getting buy/fly ratio (the ratio of the weight of the raw material we buy to the weight of the finished product) of material efficiency in the order of 5 to 10 to 1. We started on processes which brought us closer to net shape.

SLIDE 7 - This chart gives some of the inputs we consider in looking at a project for new manufacturing technology.

When we start a new project, our first goal is quality. When you fly with our engines, I want you to know that if anything can be done to make a better product, we do it! It is up to our people to cut the cost using new processes or equipment. I find that in almost all of our programs, quality, for some unknown reason, is usually a by-product, although it is our #1 goal.

By the way, for my competitors here today, the majority of the disclosures have been heavily censored. To our good customers out there, we are extending a personal invitation to visit our facility. We will show you new breakthroughs that not only give engine designers new degrees of freedom, but parts that are better as well as parts that lost longer thereby increasing productivity and cutting L.C.C.

The next slide (SLIDE 8) shows how you have to establish a breakoff point because you will dilute yourself so thin, the entire program would suffer.

My only wish is that the tools I speak about today are used to make for more "EFFECTIVE" programs.

SLIDE 9

This slide guides me in the selection of which projects we should pursue.

SLIDE 10 - Shows a summary.

The first two points, cost drivers and economic significance, are what really makes for success.

SLIDE 11 - Gives the advantages of looking at manufacturing processes rather than new products. Products usually have a limited life. In our case, a basic new engine model has a life of 10 to 20 years, whereas, a new manufacturing process keeps improving with time. Try to think of an obsolete manufacturing process. I think this is one reason that DoD is really expanding the manufacturing technology budget over the next 5 years. This is where you achieve real leverage to cut weapon system costs.

SLIDE 12 - Shows that timing is very important.

SLIDE 13 - Shows a case I ran 3 years ago. I do not remember the exact program but it demonstrates what happens on strictly military programs.

The new manufacturing programs I am about to describe were paid for out of our commercial engine sales...the military received a free ride.

SLIDE 14 - CONFINED ABRASIVE FINISHING (CAF)

The polishing and debugging of aerospace parts usually represents 30% of the manufacturing cost. It is labor intensive and has a high risk of scrap. Here we have a process that we have been merging into production for the last few years.

CAF is a non-conventional machining technique developed to deburr, radius and improve surface finish. An abrasive laden media of putty-like consistency is forced under pressures ranging from 400 to 1600 psi through a closed loop system which directs the flow into a restricted area formed by the workpiece and fixture. By proper selection of media consistency and abrasive content, process pressures and cycle times, a uniform and repeatable method of manufacture is available.

SLIDE 15

The next slide shows an example of the JT9D-70 fan hub which is constructed using diffusion bonding to form an internal hollow cavity giving us the benefits of weight savings. Following broaching of the fan blade slots, a sharp edge condition is generated at the intersection of the cavity and slot which is located adjacent to finished surfaces of critical dimensions. Abrasive Finishing was found to be the only method of forming a .040"-.050" radius to insure hub fatigue life.

The tooling concept utilizes polyurethane restrictor inserts which are formed to protect and seal against the critical broached pressure face surfaces and provide a controlled gap for media flow. The abrasive media is cycled back and forth across the cavity edges to progressively generate a smooth and uniform radius on 46 slots simultaneously.

The advantage of this process is that it is machine paced and process controlled.

HOT ISOSTATIC COMPACTION OF POWDER METAL ALLOYS - SLIDE OF HIP

Last year, we put into production the largest, most sophisticated Hot Isostatic Press in the world for turbine and compressor disks.

In December, we received FAA certification for JT8, 1st Stage Turbine Disk used in the 727, 737 and DC9 aircraft.

SLIDE 16

This slide shows the wire wound press. It can take parts 45" in diameter by 79" high. With HIP, you usually save 25% plus inventory cost with better quality and more consistency.

With hot isostatic consolidation of powder metal, you can develop new alloys never before possible because they were limited by the solubility of one element in another. All our alloys in use today were designed 15-20 years ago, before the energy crisis, political disruptions, etc. All alloys designed then were designed to be castable, weldable, forgeable, etc. Today, with HIP'ing, we do not have these limitations. Just look at the cobalt problem in Africa! The cost jumped from $7/pound to $25/pound in a month!

The real problem is that no one is <u>REALLY</u> working on the problem. Most of the alloy development, to my knowledge, is only a modification of present day alloys, not completely new ones designed around the conditions and economics in the world today.

In 1972, I predicted that in 10 years all engine disks would be made of powder. I strongly feel that I will be right on target!

SLIDE 17

Momentarily, we expect source approval for P/M preforms for GATORIZING™ or superplastic forming of 9 different P/M parts for the F-100 engine in the F15 and F16 aircraft. Here are steel pipes loaded with powder. We HIP them and then cut them up to superplastically form turbine and compressor disks. As you can see, this is a good cost reduction because of productivity compared to hot extrusion.

SLIDE 18

The next slide shows how you can improve properties of casting by closing up porosity and center line shrinkage. The greatest impact will be on engine casings, particularly those of titanium. We have had success in using this technique. It will revolutionize the casting industry!

SLIDE 19 - AUTOMATED LASER WELDING

The laser is a modern device generating a beam of light that can be optically concentrated into a spot a few thousandths of an inch in diameter.

This very intense, concentrated energy, second only to the electron beam, can be used to perform many widely diversified and useful tasks involving high energy and precision.

The Manufacturing Division of P&WA, following a period of laser development in Manufacturing Research and Development, has generated specifications and has acquired the fully automatic, computer controlled, production laser welder shown in the photograph.

Utilizing the automation capability of this advanced P&WA-specified laser equipment, Manufacturing Research and Development has developed the welding process requirements for several engine assemblies. The percent of savings over previous arc welding methods averages 64% for 12 parts for which we now have tooling. These significant savings, which result from the high welding speeds, reduced floor-to-floor time and the elimination of many postweld operations, attest to the cost reducing potential of the automated laser welding process.

SLIDE 20

Photofabrication for Transient Liquid Phase Diffusion Bonding is a patented P&WA process. In this process, a superalloy foil surface is doped with material that lowers the melting point. A shaped foil is made (as shown in the slide) by photofabrication... a technique used in solid state industry. This facility was put on-line last year. We have in excess of 100,000 TLP bonded parts flying. This gives you a 100% solid state bond with no heat effected zone. This will replace many welding and brazing processes.

To bond parts together, take the foil, put the parts in about 10 psi compression, heat until you melt the foil; the melting point is depressed as the dopant is diffused throughout the part. After a heat treatment, no chemistry gradient can be detected across the bond line.

This schematic is a flow diagram of the process. You can hold .001 with little trouble.

SLIDE 21

Shows a typical cost saving of using photofabrication over conventional stamping.

We have a program to make hot isostatic consolidated billets to replace hot extrusion billets to reduce cost of our compressor and turbine disks made of superalloy IN-100. They are then superplastically formed in our GATORIZING™ press. As we advance in the state-of-the-art to make as-HIP'ed superalloy disks, we can utilize the GATORIZING™ press for titanium parts.

SLIDE 22 - Shows our GATORIZING™ press.

We have an Air Force contract to design a modification of the chemistry so we can go near net shape directly with superplastic forming.

SLIDE 23 - ELECTRON BEAM WELDING (DRUM ROTORS)

Development efforts have been initiated toward electron beam weld fabrication of the 8-stage titanium drum rotor. We have demonstrated the ability of the electron beam process to produce high-integrity welds and dimensionally accurate post-weld part configuration on the latest, most sophisticated electron beam welder in the world put into use last month.

SLIDE 24

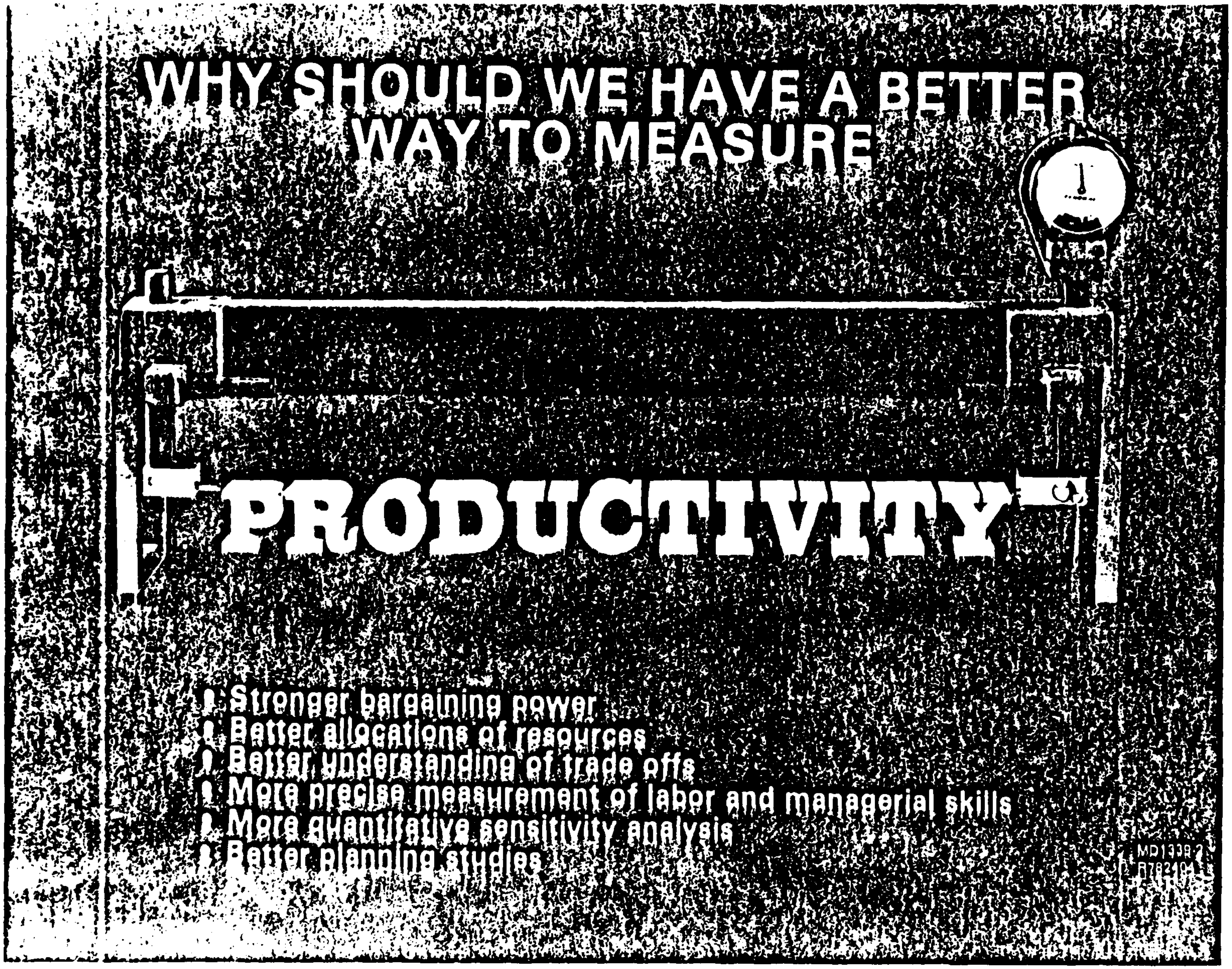
Shows a typical Electron Beam welded drum rotor for our JT10D engine.

CONCLUSION

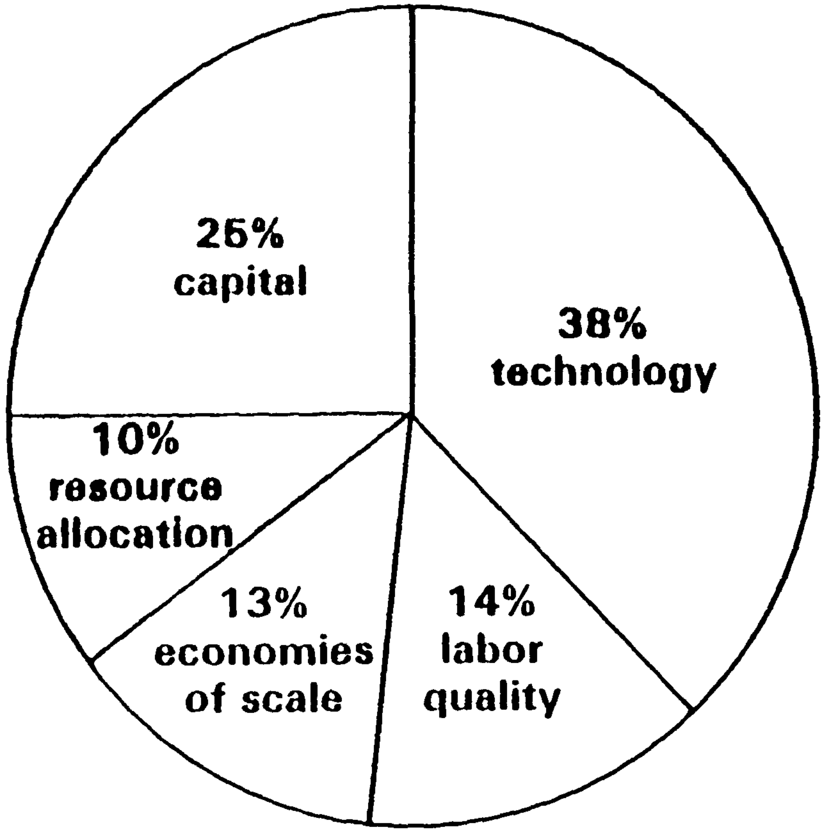
I think we covered all the elements of a good productivity improvement program. You must have technology, capital and highly motivated people.

THANK YOU.

"Productivity is a measure of management's effectiveness in employing all the necessary resources — human, natural and financial —"


WHY SHOULD WE HAVE A BETTER WAY TO MEASURE
PRODUCTIVITY
Stronger bargaining power
Better allocations of resources
Better understanding of trade offs
More precise measurement of labor and managerial skills
More quantitative sensitivity analysis
Better planning studies

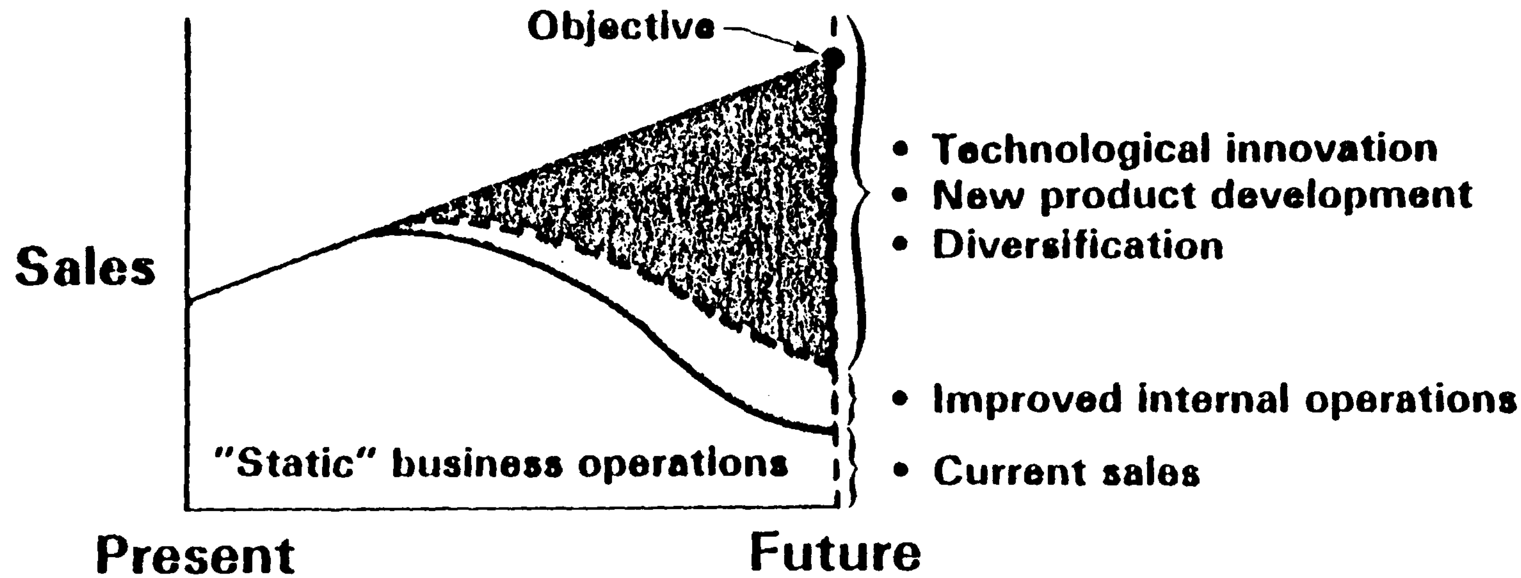
FACTORS AFFECTING PRODUCTIVITY



FACTORS INCREASING PRODUCTIVITY

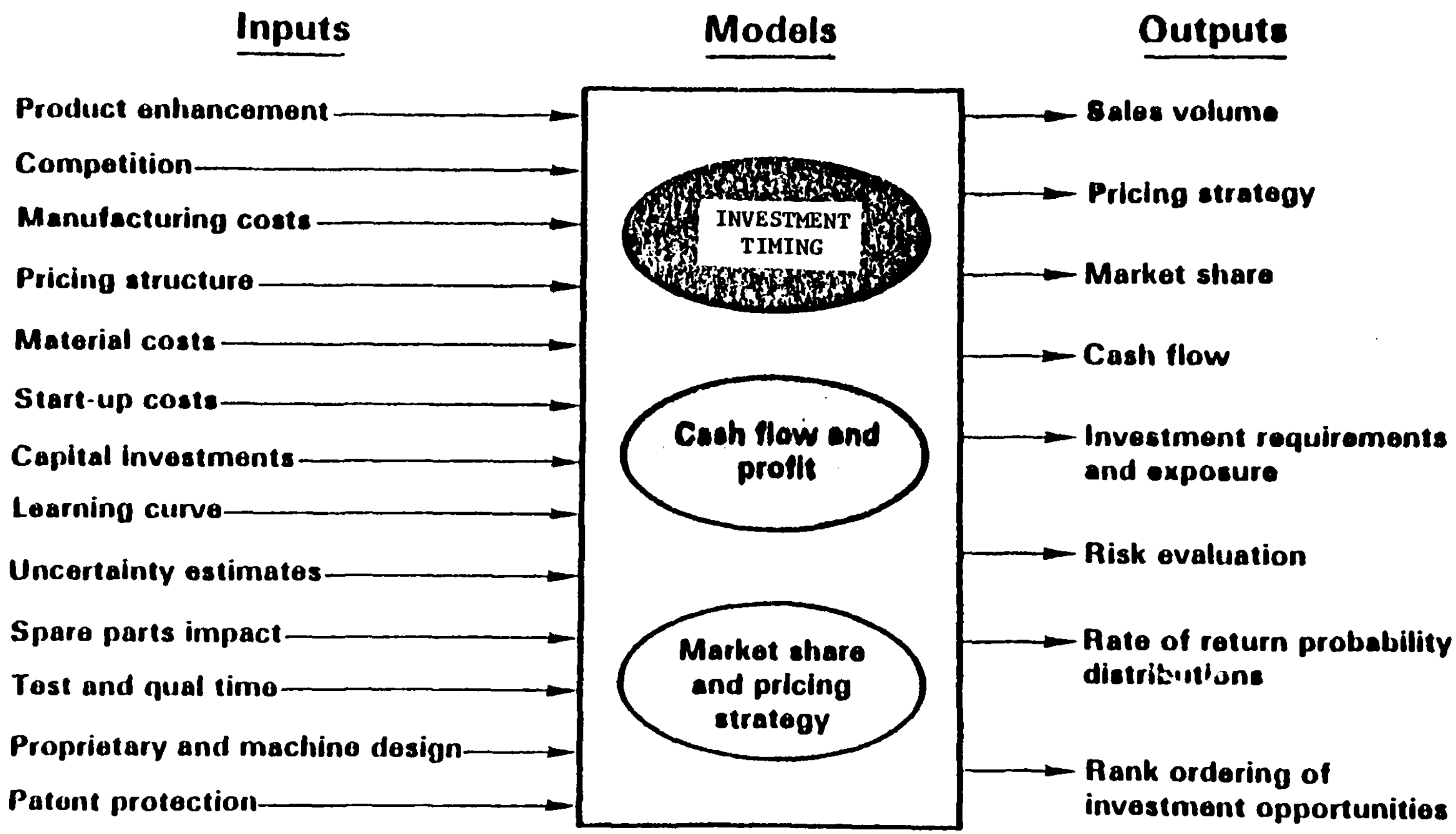
- Sound planning
- Wise investment
- New technology
- Good management
- Greater efficiency
- Acceptance of change
- Job satisfaction
- Computer technology

SALES GAP

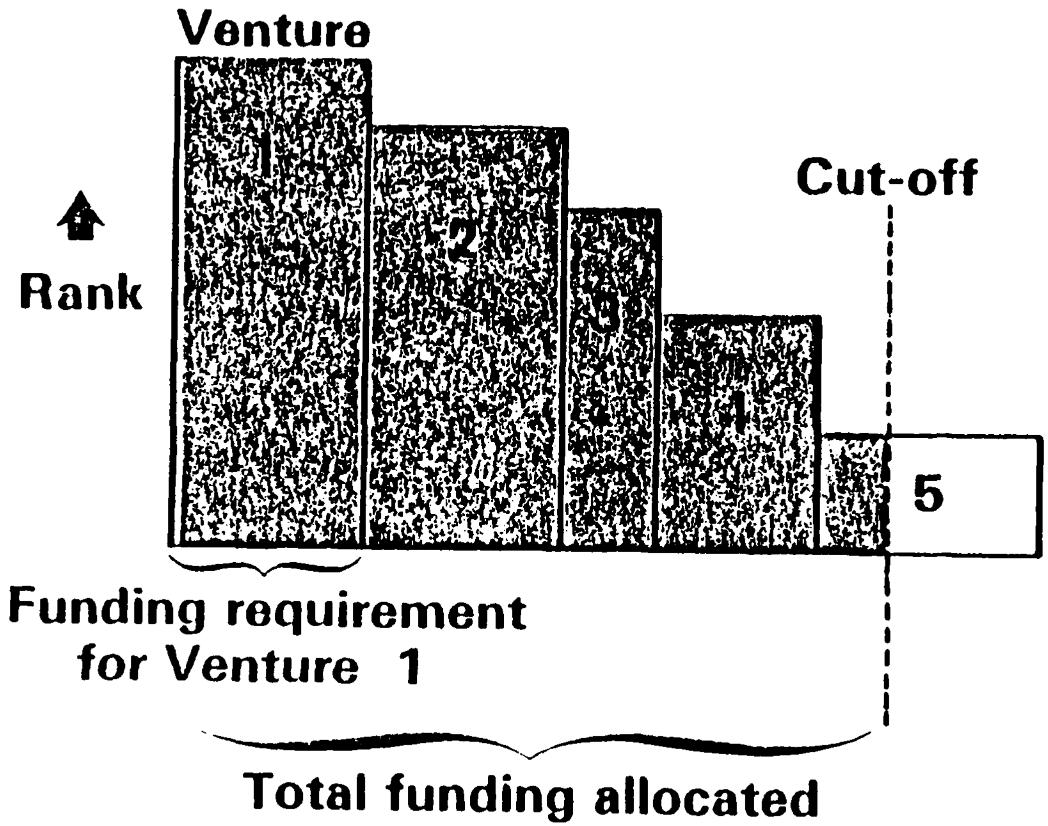


Objective
Sales
"Static" business operations
Present
Future
• Technological innovation
• New product development
• Diversification
• Improved internal operations
• Current sales

VENTURE ANALYSIS

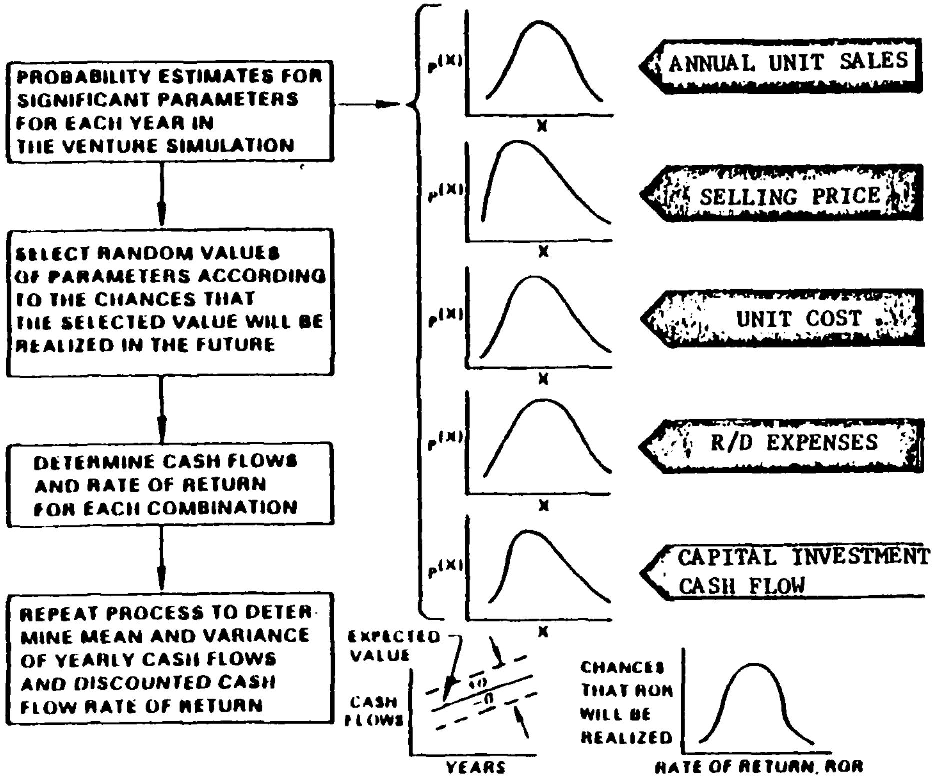


VENTURE RESOURCE ALLOCATION



CASH FLOW AND RATE-OF-RETURN

Monte Carlo simulation



p(X) CHANCES THAT VALUE WILL BE REALIZED

X VALUES OF VARIABLE

σ STANDARD DEVIATION

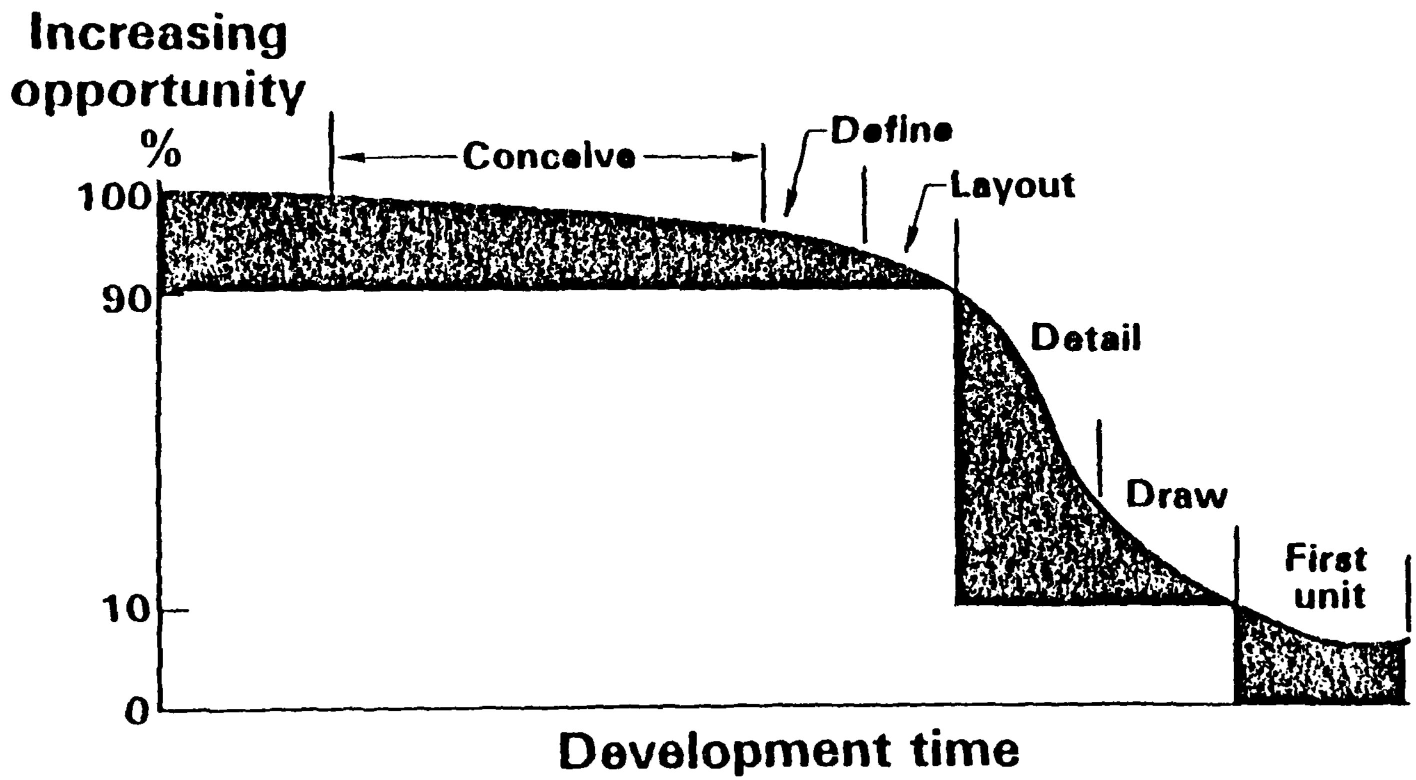
VENTURE ANALYSIS SUMMARY

- Forces detailed study of all cost drivers
- Allows full understanding of economic potential without significant investment
- Pinpoints sensitive areas
- Indicates areas which need development
- Provides recognized and accepted management tool

PROCESS DEVELOPMENT BENEFITS

- Relative to product life cycle, it is indefinite but keeps improving
- Learning curve has to be debugged only once
- Return on investment increases with time
- Applicable to many product lines
- Reduces operating costs, increases quality, reliability or safety
- Cuts product lead time

NEW CONCEPTS MUST BE INTRODUCED EARLY



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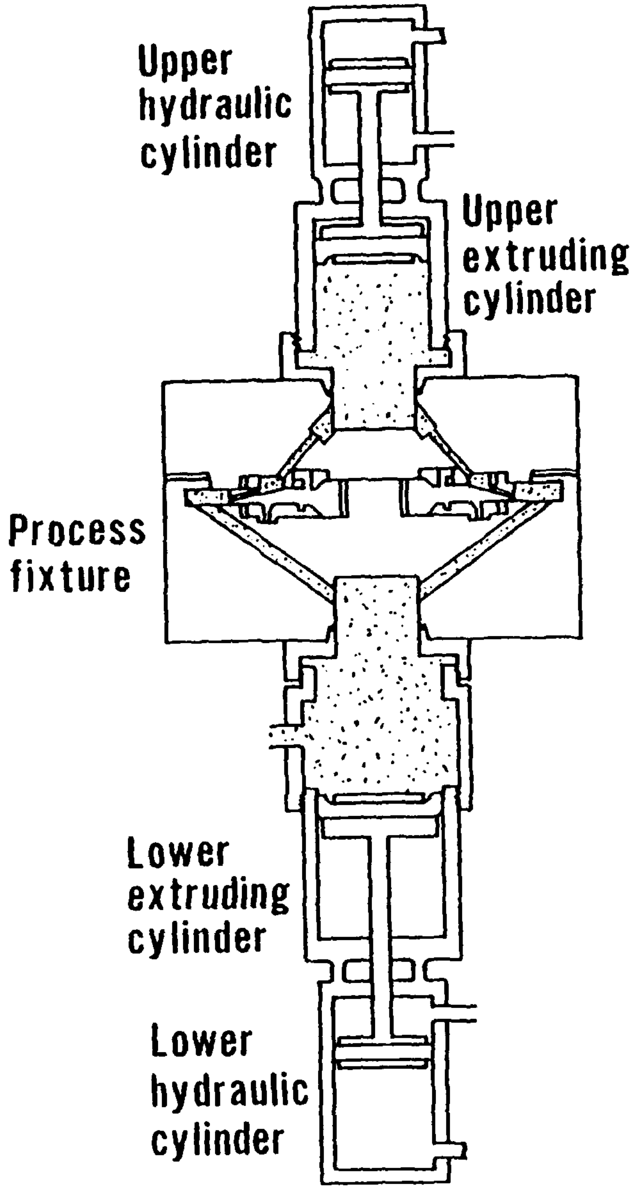

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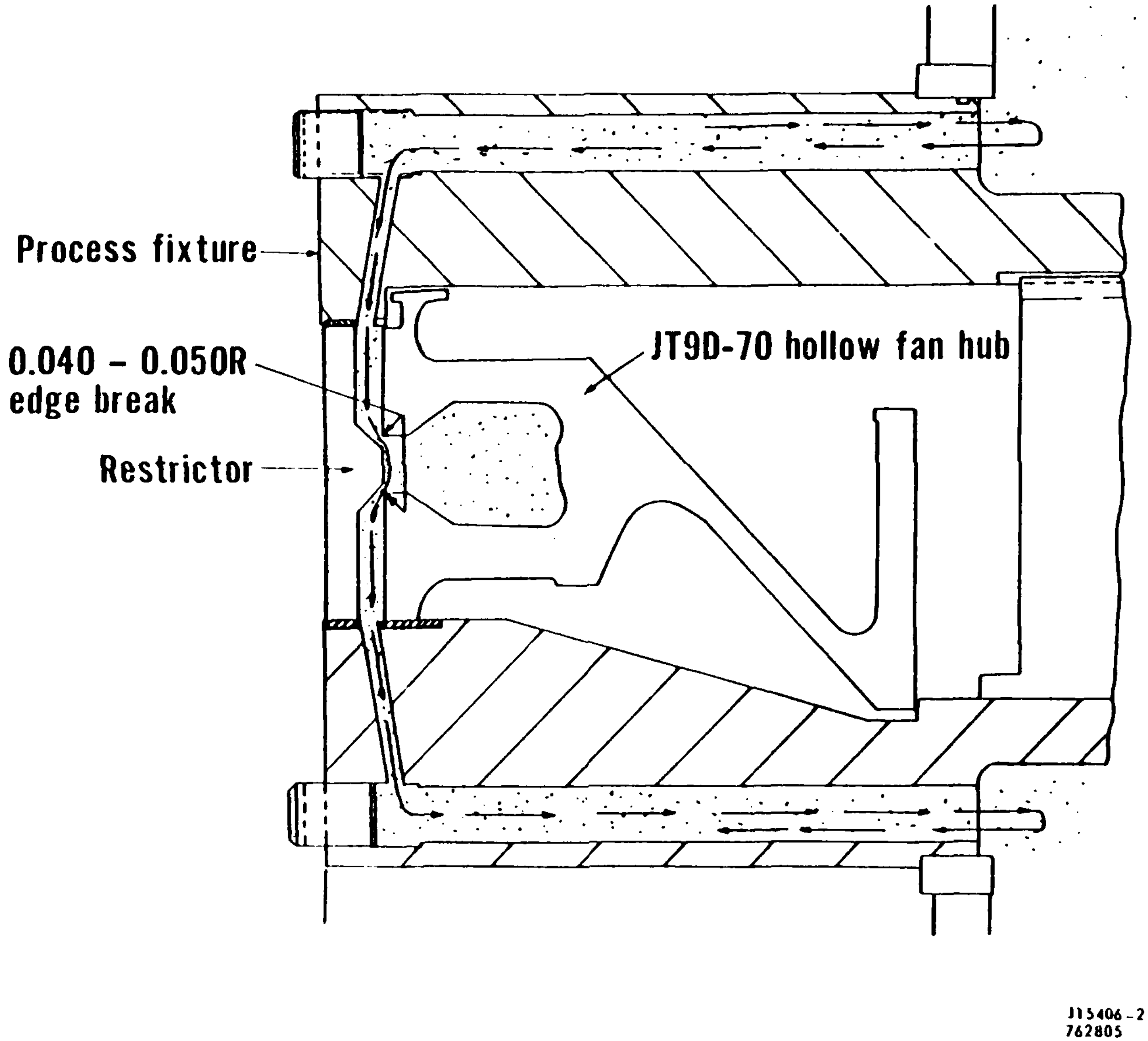
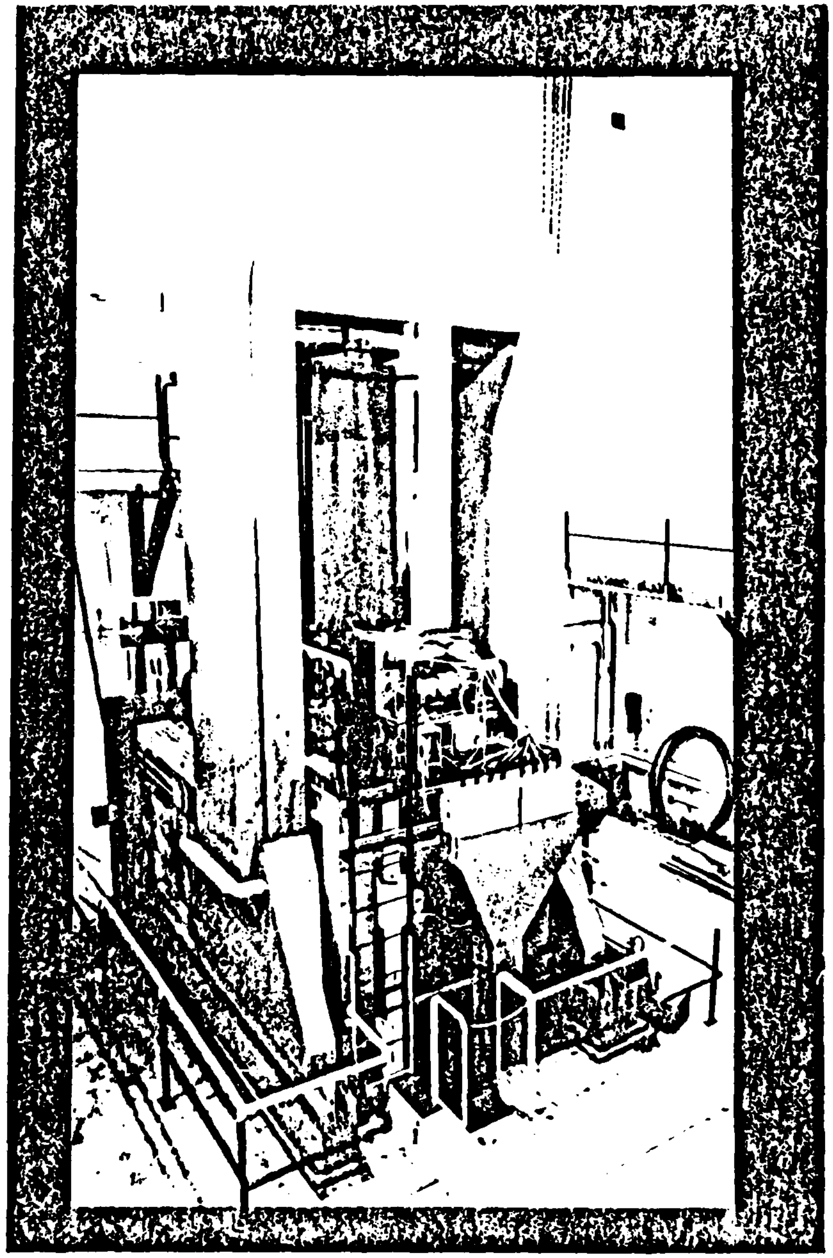
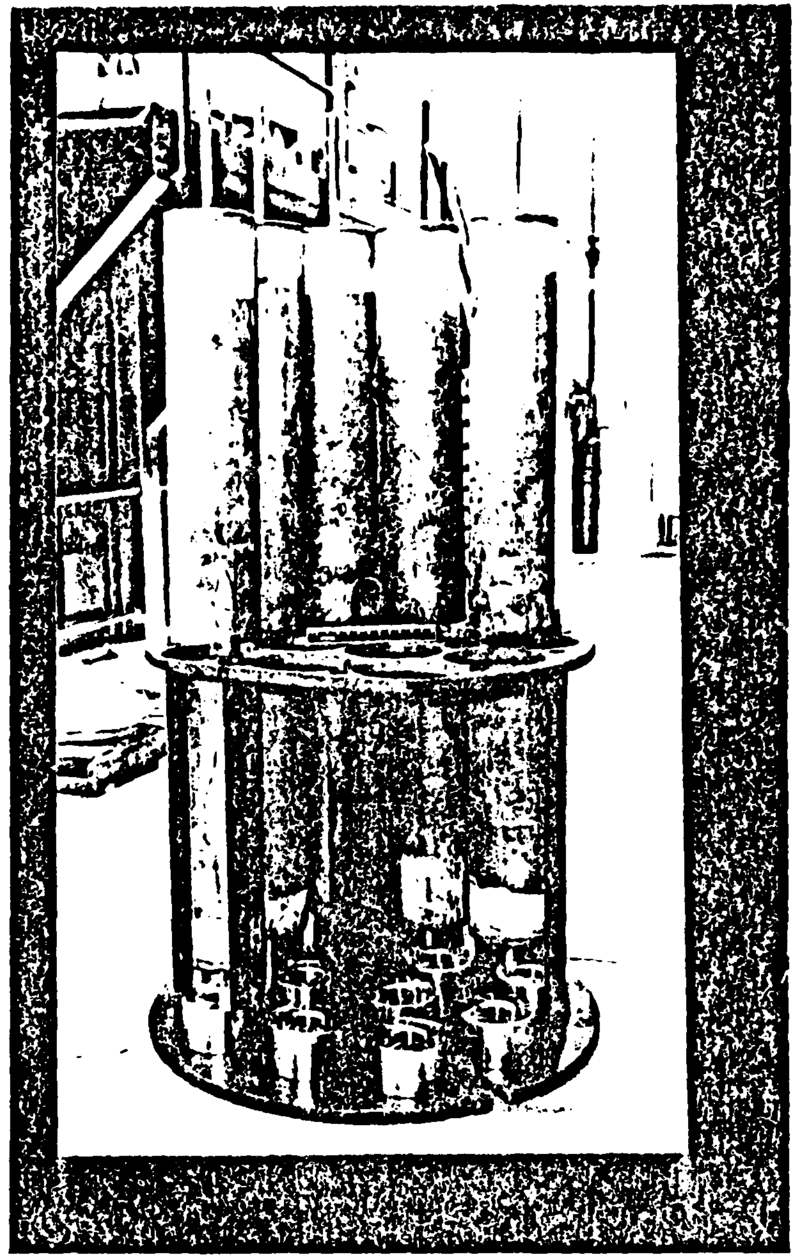

Process fixture
0.040 – 0.050R
edge break
Restrictor
JT9D-70 hollow fan hub
J15406-2
762805

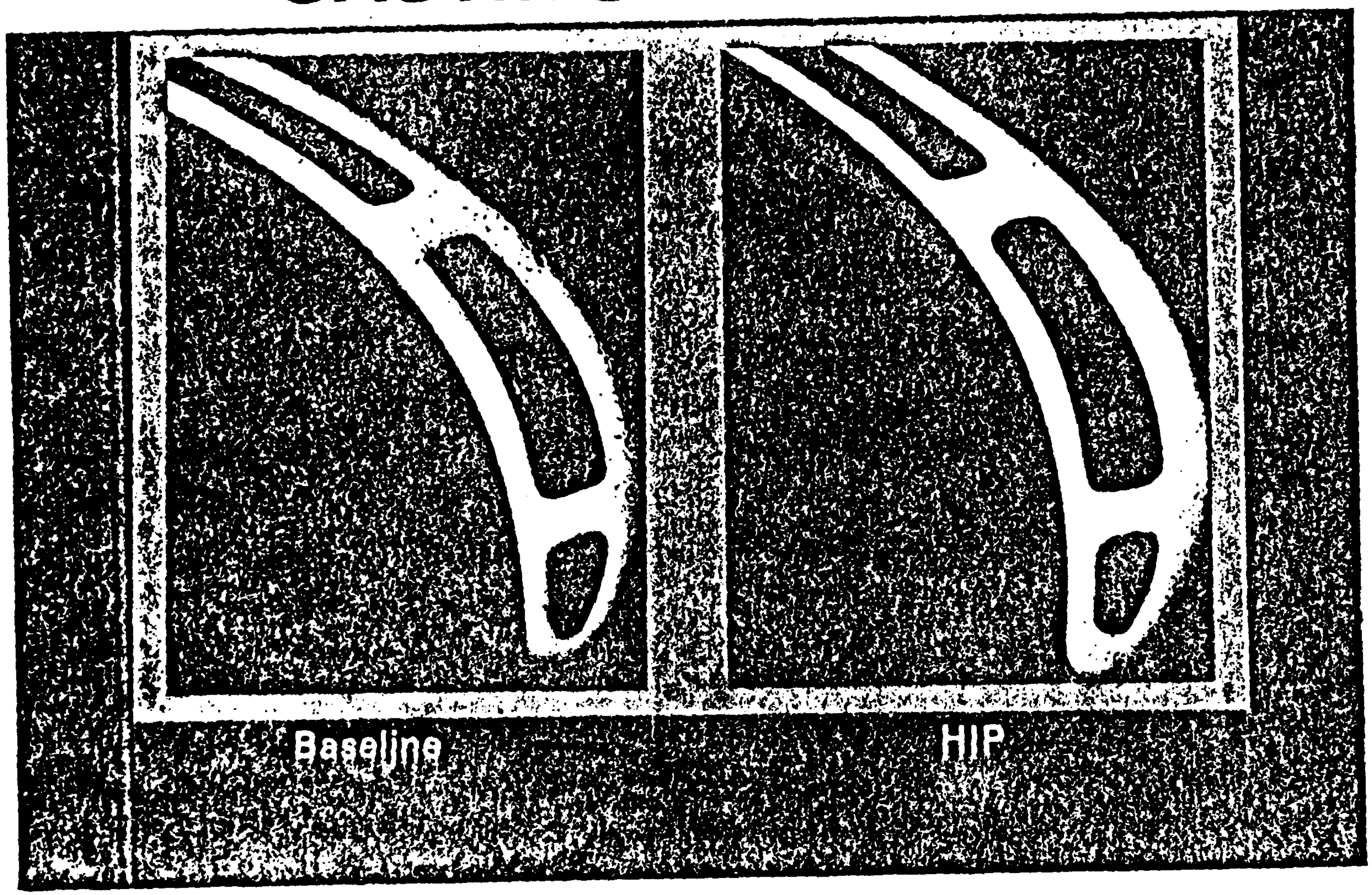
HOT ISOSTATIC PRESSING



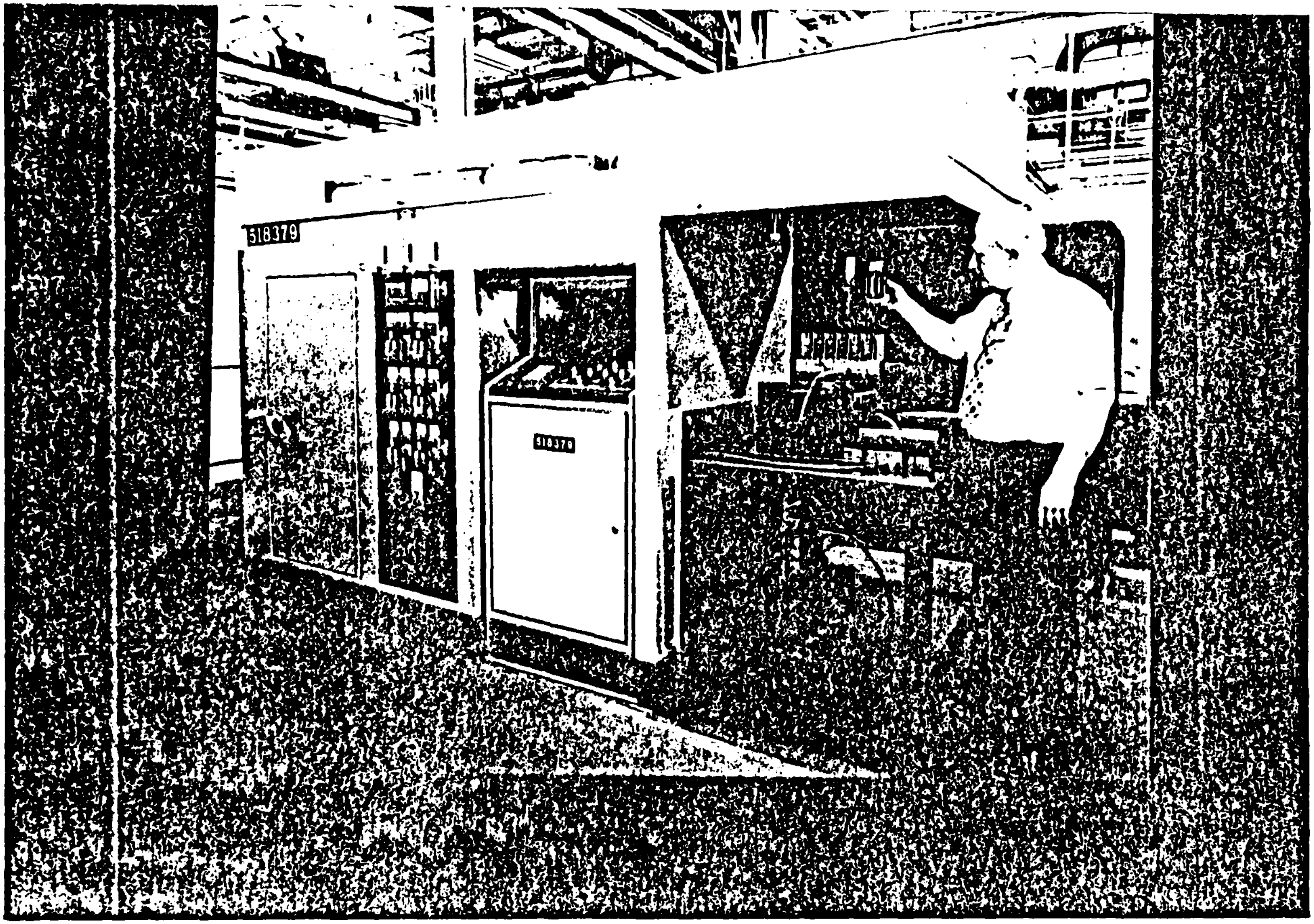
HIP BILLETS

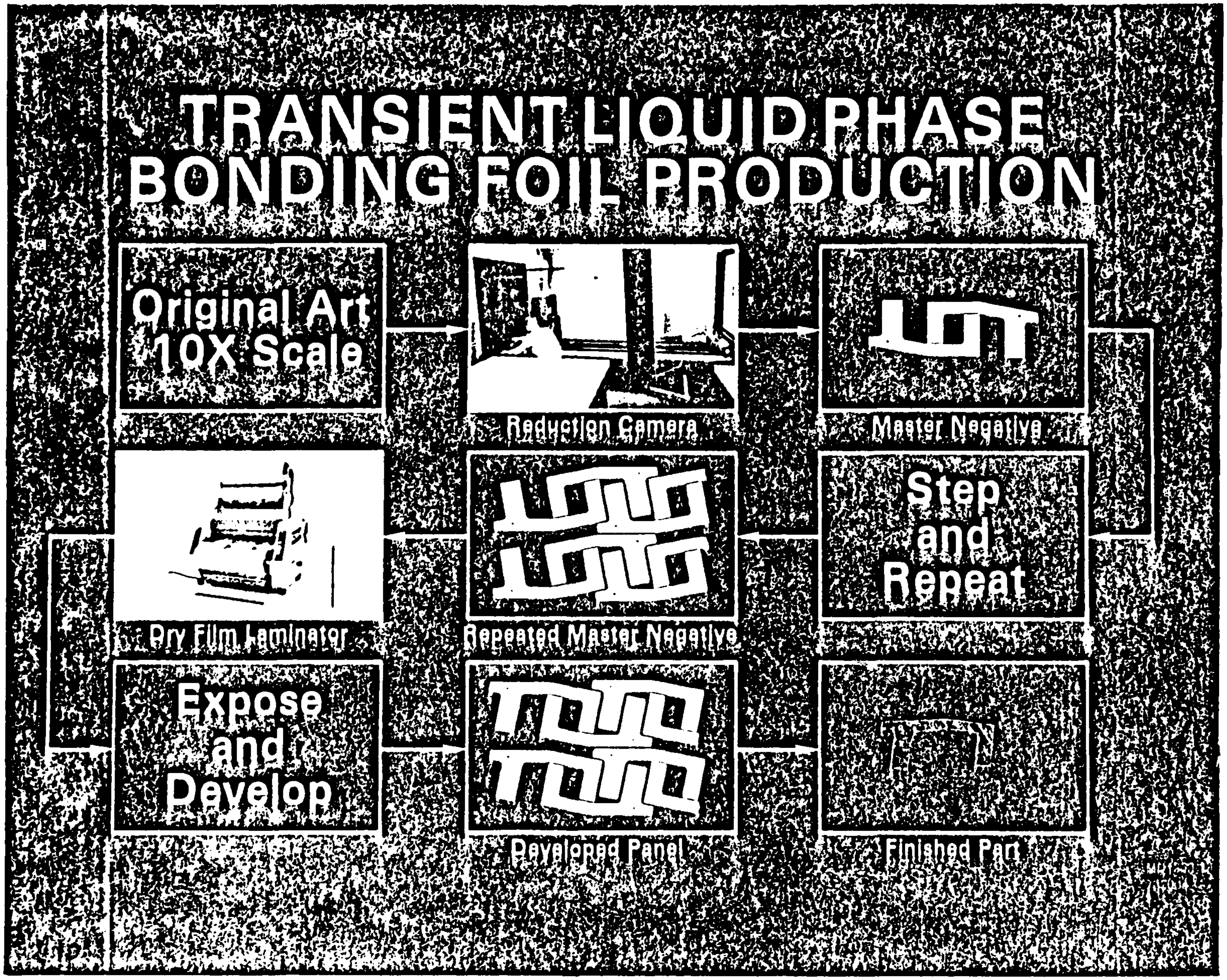


HIP ELIMINATES CASTING POROSITY



LASER WELDING

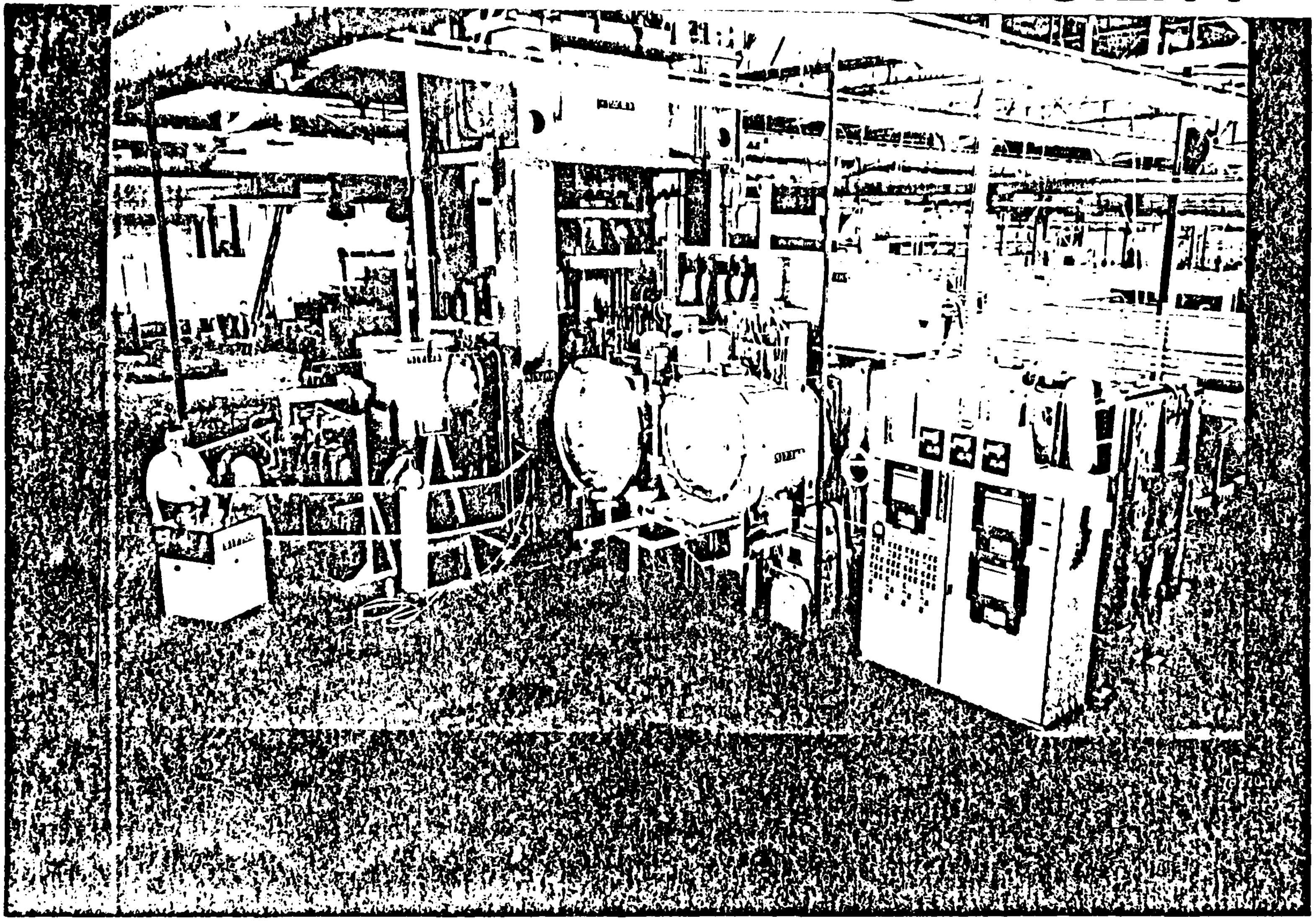


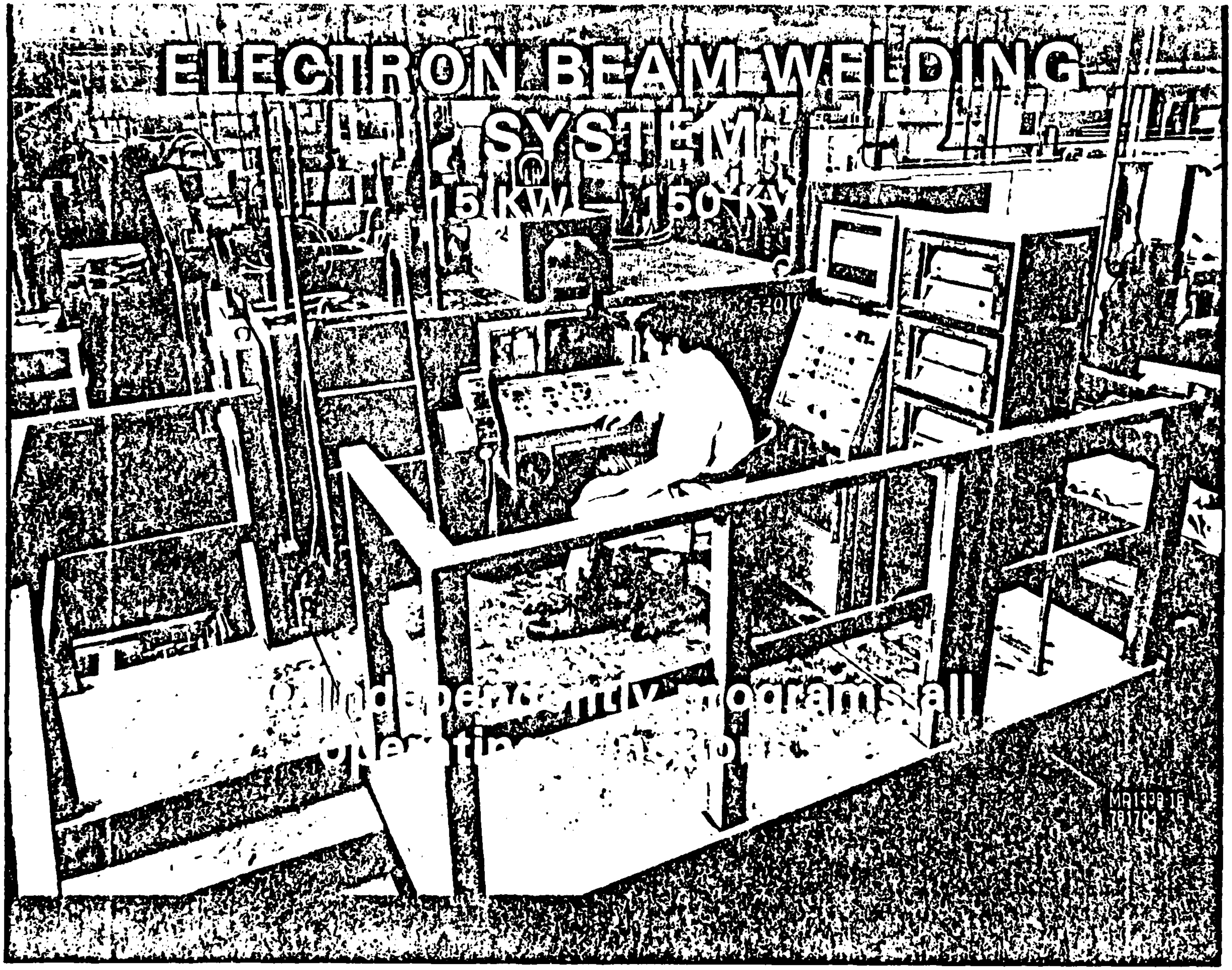

TRANSIENT LIQUID PHASE
BONDING FOIL PRODUCTION
Original Art
10X Scale
Reduction Camera
Master Negative
Dry Film Laminator
Repeated Master Negative
Step
and
Repeat
Expose
and
Develop
Developed Panel
Finished Part

BENEFITS OF PHOTOFABRICATION

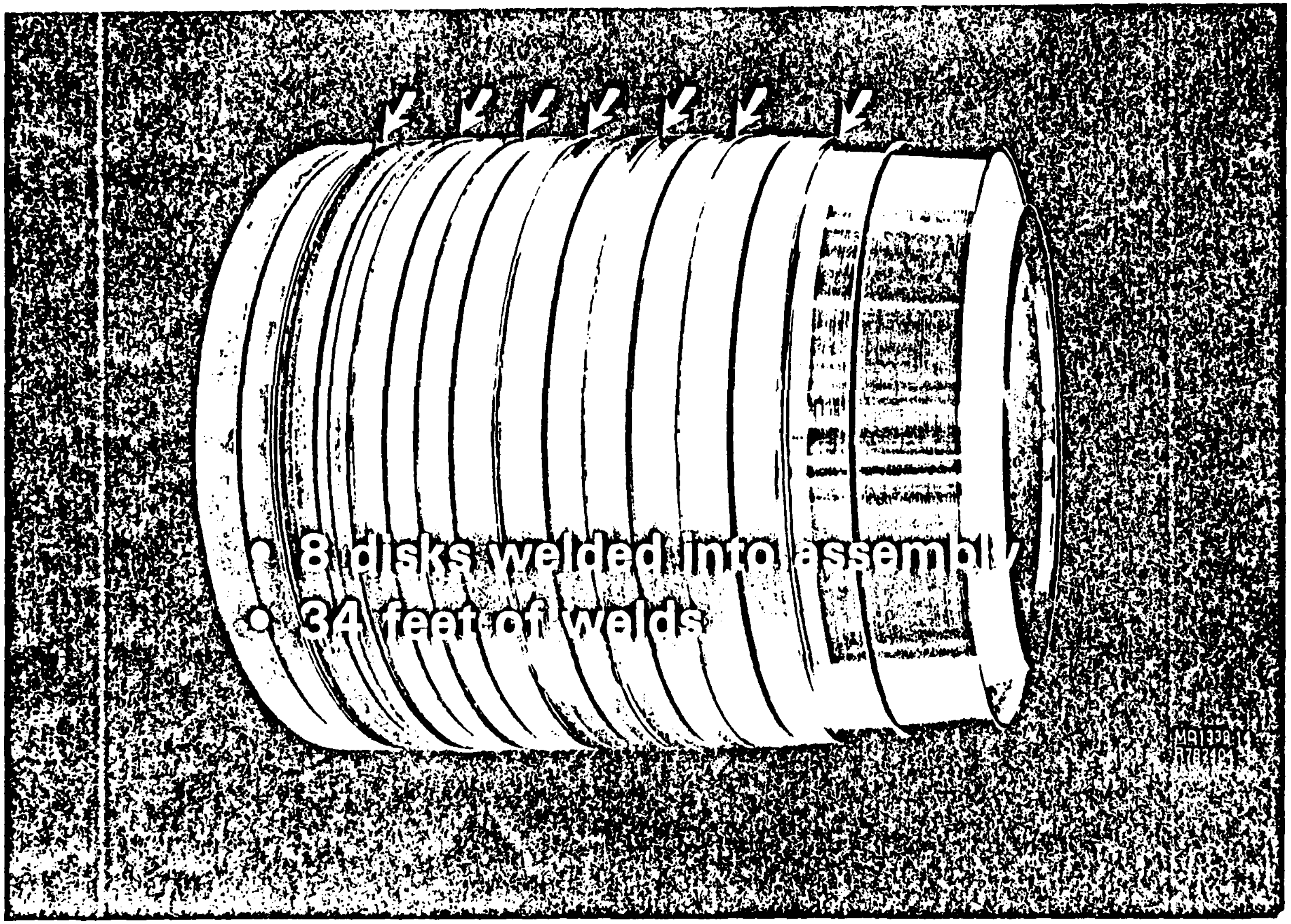
- 77% labor savings
- 40% material savings

3000 TON GATORIZING FACILITY




ELECTRON BEAM WELDING
SYSTEM
15 KW – 150 KV

JT10D WELDED ROTOR



"Long Term Warranty Growth Of An Aircraft Engine Accessary Utilizing Life Cycle Costing Techniques"

Oscar Markowitz & Joseph C. Giordano

Key Words: Long Term Warranty, Reliability, Life Cycle Costing, Warranties, Failure Free Warranty, Reliability Improvement Warranty.

ABSTRACT

This paper provides an example of utilizing LCC as an analytic tool to assess cost effectiveness of a Reliability Improvement Warranty contract. The real life contract[1] under examination is a show case example and its mid course evaluation has been reported[2]. The material for this paper was drawn from that report.

The method and approaches for the LCC analysis is described. The end results are documented. Within the LCC analysis was the utilization of the ASO escalation model, previously published[3], and described in this paper to the extent of showing how it was used.

INTRODUCTION

There have been very few DoD contract experiences to date within which a buyer-seller together had to live within an established life cycle cost. Reliability Improvement Warranties (RIW) offer this experience since they are long duration contracts, generally 5 or more years, and they are generally based on cost effectiveness studies utilizing forms of LCC modeling which form the basis for the subsequent contract fixed costs. The example used for this paper involves a case history (to date) of just such use for LCC. In the formulation stages (1972) LCC studies were made by the Navy with the potential contractor's participation. These studies made clear that the driving function of LCC would be the actual field reliability. Should this field reliability be capable of growing at least 25% over a 5 year in service use, utilizing RIW contract techniques, then there was a potential for RIW to be more cost effective than any other support alternative available to the Navy.

This LCC result was in fact sold. A RIW contract was made between the Navy and the contractor, Abex, which was priced on the basis established by the LCC, plus added assurance of cost effectiveness to the Navy by making the fixed price reflect a contract end point of 50% reliability growth. 1977 was considered the approximate mid point of this Navy contract with Abex. Thus it was an appropriate time to evaluate results to date and reexamine the LCC studies in a test of cost effectiveness both to date and to the projected end of the contract. A report on this mid contract evaluation was published[2] which included the actual out of pocket LCC costs for the contract compared to a LCC analysis of a Non-RIW alternative. This paper concentrates on the development of the above LCC comparisons utilizing material and abstractions from the reference 2 report.

LIFE CYCLE COSTS

The real life costs engendered by the RIW contract[1] were fixed by the terms of the contract and are shown below. The Navy payments to Abex were based on the projected time distribution of Abex costs resulting in a "pay as you go" payment schedule. This is shown in Table I below:

TABLE I. RIW CONTRACT N00383-73-C-3318
PAYMENTS AND SCHEDULE

	TOTALS			DATES	
	PRICE	UNITS	RUN HOURS	SIGNED	CONTRACT TERMINATION
Basic Contract - Lot I to IV	$346,444	258	387,000	Apr 73	6 Yrs.
MOD 00007 Lot V	1,061,772	354	531,000	Aug 74	6 Yrs.
MOD 00009 Lot VI	1,308,547	487	730,500	Aug 75	6 Yrs.
MOD 00012 Lot VII	1,488,247	587	880,500	May 76	30 June 1982
MOD 00013 Lot VIII	1,595,344	674	982,560	Aug 77	15 Apr 1983

TABLE I: RIW Contract N00383-73-C-3318
Payments and Schedule

The costs shown in Table I are actual "out of pocket" costs from the start of the contract. Other Navy costs inherent in total system logistics operations are not included since their effects are considered secondary for the purposes of this LCC model. The biggest cost driver by far is the actual field reliability, which for this case is inclusive for all removals regardless of reasons for removal. The major LCC cost consideration for any removal then becomes the sum of hardware costs to fill the hole in the aircraft and to prepare the removed unit for ultimate use to successively fill a hole created by another future removal. Thus field reliability and field reliability growth must look at all reasons for removals as well as logistics support to insure continuity of aircraft operation after a removal for both of the following LCC alternatives.

a. The real life situation for RIW and

b. The most likely alternative should RIW not have been available or utilized.

Reliability Projections:

The LCC study considers the most likely reliability which would have been achieved in an environment of organic and/or commercial overhaul without any reliability growth incentives. The most likely set of conditions to be included for such non-RIW alternatives are as follows:

a. Commercial overhaul of the pump by Abex. This condition was considered most likely because a 400 HP drive stand was not fully developed by the Navy and thus not available for Navy depot use.

b. Each area of RIW improvement would not have been attained. This assumption, borne out during the history of many other aircraft engine driven pumps, is most likely because the Abex beginning mean flying hour time between field returns would have been considered reasonable.

c. Every major failure mode was considered separately in the non-RIW alternative as continuing at the same rate as established by early field returns prior to RIW improvements becoming effective.

d. All remaining failures not included in c. above were grouped together and analyzed similarly, but as one group, and added to the modes of c. above, to provide a total rate of return for the non-RIW alternative.

e. An average cost of all returns to depot was developed based on actual present costs, then de-escalated to the starting year and escalated for future years. The "test good" returns were included as part of the average cost per return.

The following 5 engineering improvements (EI) are considered:

a. Sheared shaft

b. Pump leaks (other than shaft leak)

c. Test good

d. Leaking front seal (shaft)

e. Combined EI, other than above

(1) Torsion spring pocket wear

(2) Quick Disconnect (QD) seized in port cap

(3) Oscillations/fluctuations

(4) Hanger arm/mounting flange interference

(5) Other random causes

Each of the aforementioned categories were reviewed for the number of pump returns and the total number of cumulative flight hours for each time period reported. The data for each cause of return was plotted to show the trend of performance for each type of return under the RIW concept. A sample graph for (b) above is shown in Figure 1:

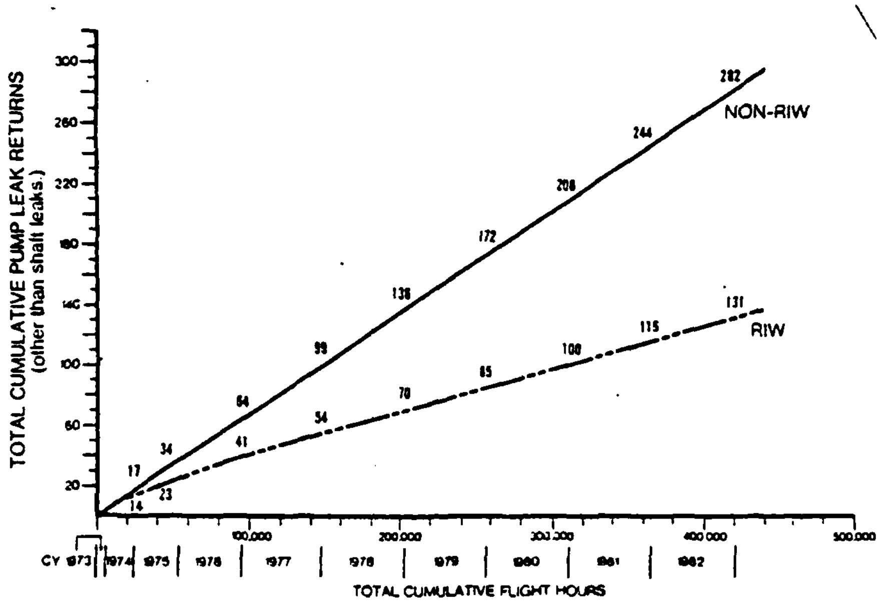


FIGURE 1: FLIGHT HOURS AND PUMP LEAK RETURNS

In the initial phase of recognition of the immediate problems along with the introduction of engineering improvements, the graphs showed a downward trend for the number of returns with an increase of flight hours between returns. In addition, these graphs were used to develop a non-RIW condition by extending the initial slope, before RIW engineering improvement, and using this projection to show the trend of returns for non-RIW. In all cases, the slopes for both RIW and non-RIW were extended to contract anniversary year (CY) 1982 in order to develop future data to show the differences between the RIW and non-RIW returns for each of the listed categories. These differences were used to calculate the cost of the non-RIW alternative. Detailed cost planning sheets were prepared from each engineering improvement graph of return slopes for RIW and non-RIW to document the magnitude of the dollars differences.

All but one of these categories listed have complete supporting return data. The last one listed, "Combined EI", was developed indirectly from engineering improvements made other than the major ones, and the analysis of disassembled repaired depot units. Because of the latter and of the small number of known returns and the only date available was the date when the improvements were incorporated, it was necessary to combine those remaining returns into one graph.

The 5 engineering improvements listed relate directly to 80% of the 208 serialized pump returns (166 each) received by Abex during the period of 3 April 1973 to 31 March 1977. Forty-two returns (20%), cannot be related directly to any one specific engineering improvement for the remaining 6 separate malfunctions listed.

These 20% returns, 42 identified, were plotted cumulative returns versus cumulative flight hours (FH) and shown in Figure 2 below.

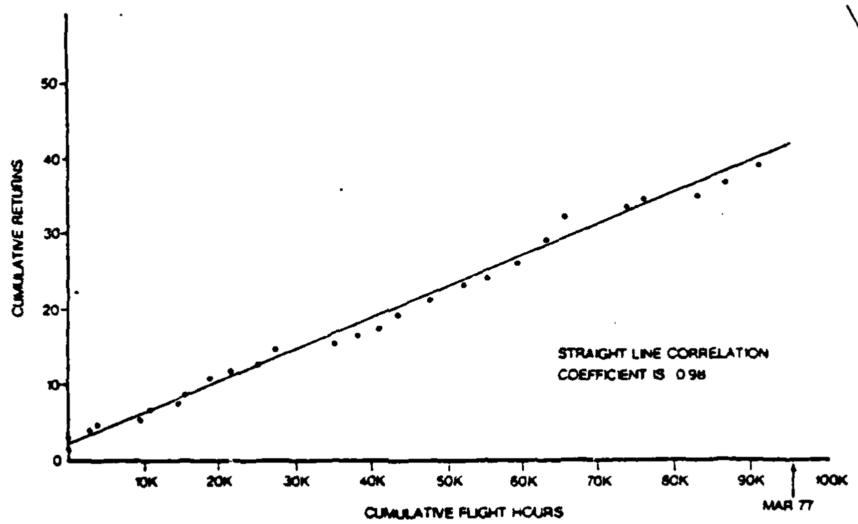


FIGURE 2: 20% RESIDUAL RETURNS (RANDOM)

The straight line correlation coefficient (CC) was determined as 0.98. Texas Instrument Trend Line Analysis program #BA1-10 as listed in their 1975 Program Manual BA1 Basic Library was used to calculate the CC. Hence, a 98% confidence exists for the linear relationship of cumulative FH and cumulative returns. This linear relationship implies a constant failure rate which is a characteristic of random type failures on an exponential probability distribution. Hence, these 42 random returns were not influenced by the contractor's RIW efforts and would, in fact, remain intact in a non-RIW alternative. This group when projected at the same slope would remain the same both for RIW and the non-RIW alternative. Therefore, no cost differences between RIW and non-RIW exists for this residual random category of returns.

The above represents an analysis for anticipated non-RIW reliability based on separation of components into manageable elements. This analysis resulted in a prediction of returns for that alternative. Another independent analytic approach was to look at the total system start up return rates and project them without reliability improvements. This was done and results of these two analytic approaches correlated closely.

Alternative Costs:

The next phase considered for cost differences was the non-RIW alternative cost to repair pump returns. The first thing to be considered was the availability of Hydraulic Test Stands to test the Abex Model AP27V-5 hydraulic pump. Presently, there is a current contract to develop a hydraulic test stand. From all indications, there won't

be any production hydraulic test stands accepted before 1982. Based on these findings, the cost of repair will be predicated on the use of commercial overhaul at Abex.

To assist in the development of the cost of repair, RIW Program Pump Reliability was projected and analytically transformed to determine the number of non-RIW pump returns. The slope for RIW was plotted with known mean pump hours between unscheduled removal (MPHBUR) hours and pump hours for the period of 31 Mar 74 to 31 Mar 77. This curve was projected to cover the period of 3 Apr 73 through 31 Mar 83. The non-RIW slope was developed by taking a 5% yearly increase from the real life starting 488 MPHBUR value to obtain projections to 31 Mar 83. This is truly a conservative approach used in developing the non-RIW curve. In other aircraft cases, a slope of MPHBUR resulting when no RIW incentives exist has been either constant or with some degradation. Table II below shows the quantity of pumps returned for repair for the RIW and within a non-RIW alternative:

TABLE II: SYSTEM RETURNS

Avg. Interval MPHBUR		Pump Hrs. Within Interval	Returns Within Interval				Time Interval	
RIW	NON-RIW		Non RIW	RIW	*	Cumulative Returns Difference		
575.5	500	17,949	36	32	4	4	Apr 73-Mar 74	CY 73
750.5	524.5	55,555	106	75	31	35	Apr 74-Mar 75	CY 74
939	549.5	73,269	134	79	55	90	Apr 75-Mar 76	CY 75
1143.5	574.5	110,394	193	97	96	186	Apr 76-Mar 77	CY 76
1136	599.5	109,335	183	82	101	287	Apr 77-Mar 78	CY 77
1525	622	135,540	218	89	129	416	Apr 78-Mar 79	CY 78
1712.5	653.5	135,540	208	80	128	544	Apr 79-Mar 80	CY 79
1900	687.5	135,540	198	72	126	670	Apr 80-Mar 81	CY 80
2100	712.5	135,540	191	65	126	796	Apr 81-Mar 82	CY 81
2300	737.5	135,540	184	59	125	921	Apr 82-Mar 83	CY 82
	NON-RIW RETURNS		1651					
	RIW RETURNS			730				
	NON-RIW MINUS RIW RETURNS					921		

*Interval Difference

The three prime cost elements considered were:

a. Costs associated with the repair of returned units at a depot.

b. Cost associated with removal and return of removed units through the fleet maintenance levels.

c. Costs associated with spares levels established to provide fleet support (directly related to removal rates).

Since the non-RIW alternative would have of necessity been limited to the Abex depot then the depot costs were determined by the current actual costs to repair a returned unit at Abex less costs allocable to reliability improvement effort. This was considered a base 1976 cost, de-escalated for prior years and escalated for future years of consideration for the LCC analysis. Escalation (de-escalation) was modeled from an ASO model developed for RIW pricing adjustment considerations[3]. Reference 2 provides the applicable detail of costs and escalation.

Operations maintenance costs were considered because of the additional non-RIW alternative removals. Man-hours for removals (maintenance actions) were multiplied by per hour costs established by the Bureau of Naval Personnel for the current base year. That base year cost was escalated for future years and de-escalated for past years.

A third and important element of "out of pocket" costs was the change in inventory required to support the increased removal rates for the non-RIW alternative. Currently, the spares program required to support the RIW Program is most favorable. The total number of procured spares (with RIW) to date is 138. To determine the dollars required for non-RIW spares growth, it was necessary to develop the quantity of spares required to support the F-14 aircraft under the non-RIW support alternative. This was done by generating the number of flight hours and the average reliability value (MPHBUR) (non-RIW) for each fiscal year from 1 Jul 73 to 1 Oct 83. The inventory manager then provided standard support spares requirements as a function of reliability and flying hour program. The prices for the non-RIW spares was reconstructed from the prices paid for the RIW spares. Explanation of the development of these prices is as follows:

a. A cursory review of the prices for RIW spares showed that the prices varied with the quantity purchased and with the inflationary cost of each successive year.

b. The quantities developed for the non-RIW spares were in most cases about twice the quantities purchased for RIW. Therefore, the cost for non-RIW spares should be less based on the larger ordering quantities. However, this is offset by the inflationary costs incurred during the spares procurement year in question. Abex concurred that a larger number of spares purchased would contribute towards a lower unit price. Hence, a reasonable assumption from Abex price schedules was made that the reduction of unit price on larger non-RIW spares quantities equals the yearly inflationary percentage increase for the procurement year in question. In this way, the unit cost reduction accompanying a large quantity spares order should offset the economic inflation of the outyears spares buy. Thus, it is anticipated that each oppositely directed cost driver (spares quantity and inflation) would tend to cancel each other toward an equilibrium price.

c. To implement the above assumption, the RIW price was de-escalated for those non-RIW spare quantities that were two or more times greater than the RIW spares through FY 78. Hence, the percentage inflation for the year when the spares procurement occurred was removed. This removal of inflationary costs or a portion thereof is assumed to be the price discount associated with larger quantity spares procurements for non-RIW

vice RIW. When non-RIW spares are double or more, than RIW spares quantity, the full "inflationary discount" is taken. When the non-RIW to RIW spares quanity ratio is less than double, an appropriate proportion of the inflationary discount is used.

d. For the cost of the FY 79 non-RIW spares, an escalation factor was used since there wasn't any RIW cost data available beyond FY 78 to de-escalate. An escalation factor of only 3.5% was used for FY 79 in lieu of 7%, because the quantity of non-RIW spares was only 1-1/2 times greater than the RIW spares. If the FY 79 non-RIW spares were twice (or greater) the RIW quantity, a zero percent escalation factor would have been used, thus allowing for a full inflationary discount.

e. For the costs of non-RIW spares for FY 80, the full inflationary discount was allowed as the non-RIW spare quantities were estimated at five times the RIW spares quantity estimate. This factor of five is applicable to FY 81 and FY 82 non-RIW to RIW spares ratio (with its corresponding justification for the full inflationary discount allowed); however, it is realized that a slight increase in price would occur for FY 81 and FY 82. This slight increase is estimated at 3% each for FY 81 and FY 82 non-RIW spares costs as RIW spares costs are not available, and one would not expect for identical buy quantities, FY 81 and FY 82 spares costs as being the same.

Cost Effectiveness:

The much higher levels of reliability obtained within the RIW contract over that which could be reasonably anticipated for the non-RIW alternative has insured the present and continuing LCC cost effectiveness of the RIW. Below is Table III which abstracts the LCC analysis elements for the differences in total costs between the RIW and non-RIW alternatives for the period of 1 April 1973 to 31 March 1983.

TABLE III: Summary of Differences (Non-RIW Less RIW)

	Difference
Total Returns	+ 921 pumps
Field Maintenance Costs	+ $16,061
Depot Costs	+ $1,020,072
Spares Inventory	+ 370 pumps
Inventory Costs	+ $953,518
Total Cost Difference	+ $1,989,651

ESCALATION

In any long term analysis involving dollars, escalation becomes a major consideration. The uncertainties of current rising market prices makes it extremely difficult to project future trends. In a long term contract, such as RIW on which this paper is based, the only approach available during 1973, to the contracting parties, was for each party to

make independent escalation projections for the period involved (6 years) and negotiate a final settlement. This was done and the contract was signed based on a changing dollar amount for each subsequent year's costs by multiplying the out year costs in current dollars times the agreed escalation factors. The escalation factors which were used are listed below:

	Labor	Material	Overhead
1973	4%	5%	4%
1974	4%	5%	4%
1975	4-1/4%	5%	4-1/3%
1976	6%	5%	6%
1977	6%	5%	6%
1978	6%	5%	6%
1979	6%	5%	6%

Subsequent to the contract award, ASO developed the following concept for escalation adjustment within long term warranty contracts:

CONTRACT ADJUSTMENTS COULD BE MADE FOR ACTUAL ESCALATION BY TRADING CHANGES IN CONTRACTOR RISK DUE TO UNACCOUNTED ESCALATION FOR EQUAL COMPENSATING CHANGES IN CONTRACTOR RISK BY ADJUSTING CONTRACT PROGRAM IN LIEU OF TRADING FOR DOLLARS PREVIOUSLY PAID OR TO BE PAID TO THE CONTRACTOR. The concept was supported by development of a model which was tested against a previous RIW contract and then modified by the experience of that test. The final model was published in reference 3. A block diagram of this model with weighing factors used in the LCC of this paper is shown in Figure 3.

ESCALATION MODEL BLOCK DIAGRAM

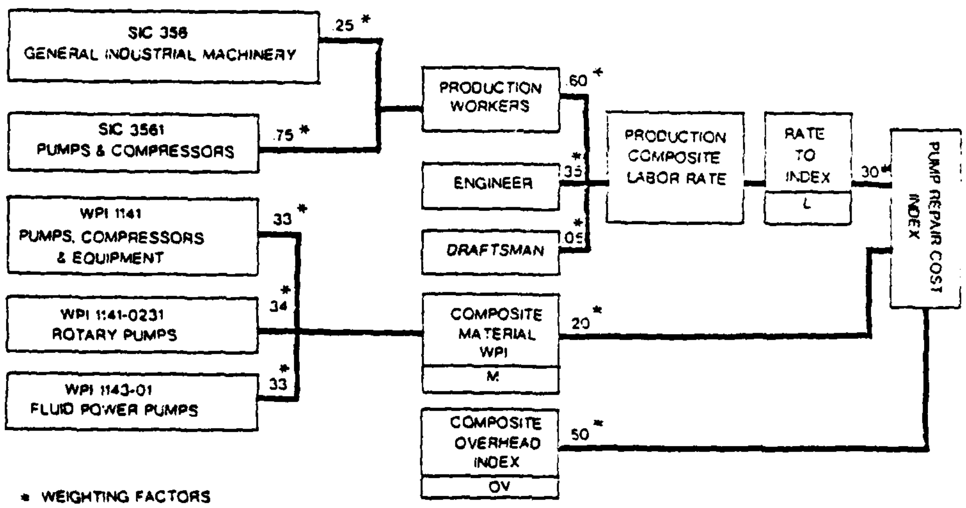


FIGURE 3: ESCALATION MODEL BLOCK DIAGRAM

As part of the RIW mid contract evaluation[2], the model was again tested against this contract to determine validity of the negotiated escalation factors. The results of the test indicated that the negotiated values were low but not to an unacceptable degree. The actual net adjustment, if this model had been applicable to the contract, would have been a reduction of warranted pump hours from 730,500 to 713,559 or 2.3%. Since this test added confidence in the model's application, it was used as a basis for escalation consideration for the non-RIW LCC development.

RIW RESULTS

The RIW contract[1] for which this LCC analysis was a part of the evaluation has produced significant results other than proof of being a cost effective support alternative. The results to date are shown below matched against contract features:

Contract Feature	Results
A. Reliability growth; 500 to 750 pump hours between returns.	A. 488 to over 1200 pump hours between returns.
B. One day turn around at Abex dock supported with pool of 25 units.	B. One day turn around in all cases with growth of pool above 25 units because of achieved higher reliability.
C. Firm fixed price.	C. No contract adjustments made. Operations remained comfortable within the established firm fixed price.
D. All returns repaired by Abex, no exclusions.	D. No exclusions requested by Abex after returns. All units repaired or replaced.
E. No buyer cost for engineering changes.	E. Three major changes; basic to 01, to 02 and to 03 configuration, many Class II changes. All changes made at no cost to the Navy.
F. A defined contractor controlled and implemented reliability program with dedicated full time engineering effort.	F. Each return inspected and analyzed by the program reliability engineer. This engineering effort is an integral part of the Abex engineering department with quick reaction time and support.
G. Regular reporting to the Navy.	G. Monthly formal reports. Quarterly engineering meetings. Annual program reviews.

H. Contract coverage for all (Lots I to IV) F-14 Aircraft.	H. Contract continuity maintained by ammendments including more recent Lots V to VIII F-14 Aircraft.

The 1973 to 1983 costs for the RIW contract will total $1,595,344. This is most cost effective since the non-RIW alternative costs have been established through LCC analysis would have been $3,584,995. Reliability growth originally established and priced with an end point of 750 hours of pump operation between returns has reached 1250 hours much before the end of the contract.

Fleet support at the time of the most current analysis reported in reference[1] has been excellent with only 25% spares as compared with other aircraft engine driven pumps which usually have spare levels above 50%. The reports of "Not Operationally Ready, Spares" have been exceptionally low for this pump, at least one order less than for other comparative pumps for other Navy Aircraft.

SUMMARY

The Abex RIW contract has afforded an excellent opportunity to examine through LCC techniques an original Navy management position in 1973, the subsequent 1977 LCC evaluation reconfirmed the wisdom of that original position and subsequent decision.

Escalation can be contractually treated while maintaining constant contractor risks utilizing the ASO model. The use of the model relieves a contractor from adding risk dollars to his costs to cover escalation uncertainties. The model can be utilized for both LCC studies as well as for long term warranty contracts.

REFERENCES

1. Contract N00383-73-3318 between the Aviation Supply Office, Phila, PA and Abex Corp. Oxnard, CA dated 2 April 1973.

2. ASO Report Number, ASO-TEE-2-77 "Mid Contract Evaluation ASO Contract N00383-73-3318 with Abex Corp., dated October 15, 1977; Defense Documentation Center Aquisition Number AD #A048244.

3. Oscar Markowitz, Joseph C. Giordano Technical Paper "Avionics Escalation Composite Index, Multiyear Contractual Clauses Adjustment with No Exchange of Dollars"; SOLE 11th International Logistics Symposium, August 1976.

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BIOGRAPHIES

Mailing address: Mr. Oscar Markowitz, TEE-A
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700 Robbins Avenue
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Oscar Markowitz since 1960 has been head of the engineering staff within the U.S. Navy's Aviation Supply Office in Philadelphia, PA. In this position he has pioneered efforts to procure aircraft spare parts in a manner which would minimize life cycle costs and enhance reliability. He fathered within the Department of Defense the long term warranties known originally as Failure Free Warranty and later renamed Reliability Improvement Warranty. During this period, he has authored more than 15 papers and studies on this subject.

Mr. Markowitz has a BS degree in Electrical Engineering (Power) a MBA degree in Operations Research and is presently enrolled in a PhD program. He has a Professional Engineering (Electrical) license in the state of Penna. and is a Certified Professional Logistician.

Mailing address: Mr. Joseph C. Giordano, TEE-3
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Joseph C. Giordano graduated from Drexel University in 1968 with a Master of Science degree in Mechanical Engineering. From 1962 through 1973, he was employed by the Naval Air Engineering Center (NAEC), Philadelphia Naval Base. During these eleven years he worked as project leader on landbased and shipboard catapult designs for R&D, and with Aircraft Carrier Compatability Studies.

Upon the NAEC move from the Philadelphia Naval Base to the Naval Air Station, Lakehurst, New Jersey, in June 1973, he secured a position as General (Mechanical) Engineer at the Naval Aviation Supply Office in the Engineering Assistance Branch. His current duties involve Reliability Improvement Warranties, Quality Assurance, Inspection Systems/Programs, Statistical Studies on Aircraft Maintenance Actions, Variable Escalation Clauses, and special staff studies.